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Lee

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(54) **EMBEDDED MODE CONVERTER**

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(51) **Int. Cl.**⁷ **G02B 6/14; G02B 6/26**

(52) **U.S. Cl.** **385/28; 385/43; 385/50**

(58) **Field of Search** **385/27-29, 39, 385/43, 50, 130-132**

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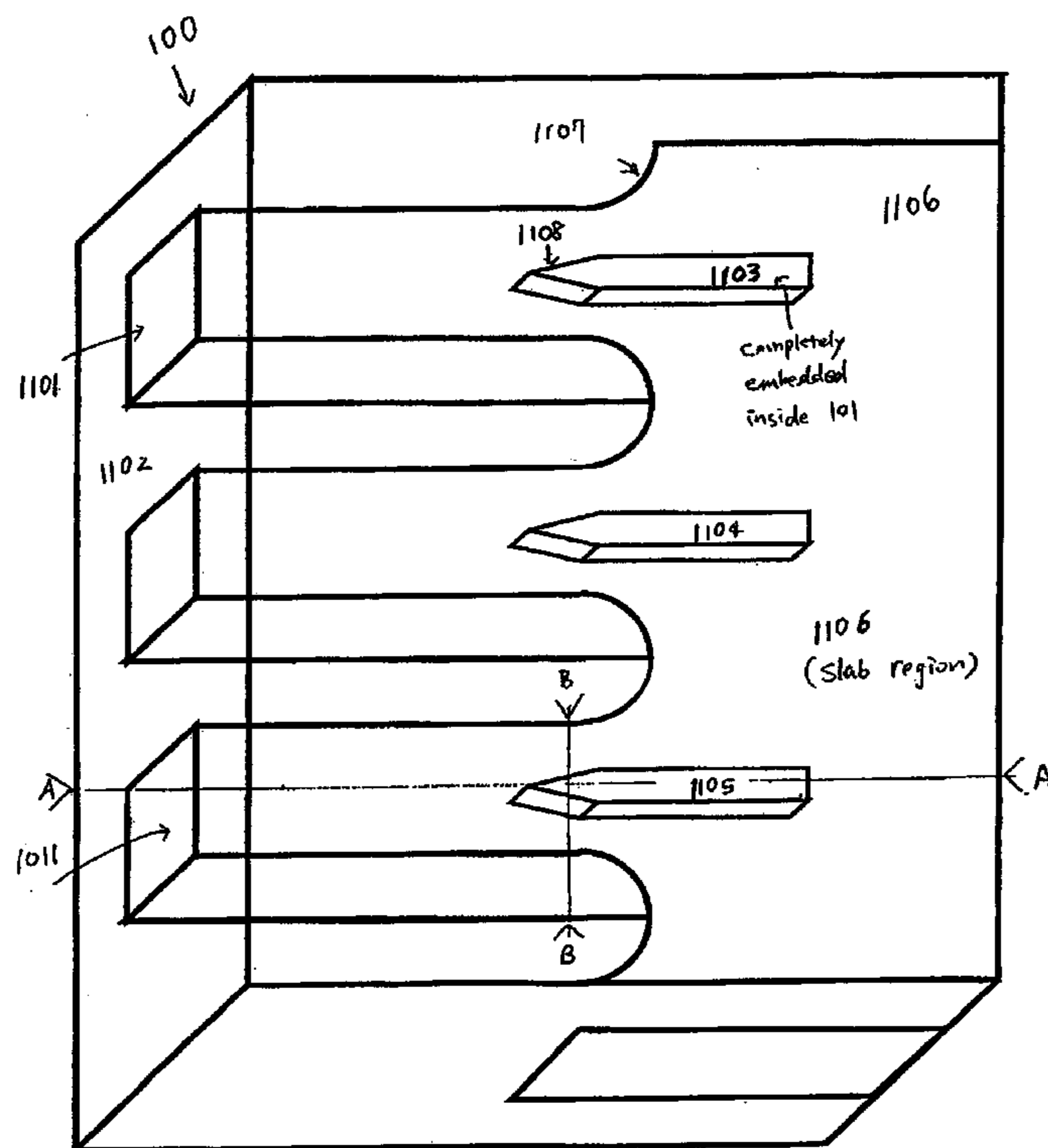
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(57) **ABSTRACT**

An optical mode transformer. The optical mode transformer features a low index core, a high index core having a first tapered region, with the high index core embedded within the low index core and with the low index core serving as a cladding for a waveguide defined by the high index core embedded in the low index core, and a cladding layer surrounding the low index core, with the cladding layer including one or more materials with different refractive indices than those of the low index core and high index core.

35 Claims, 17 Drawing Sheets



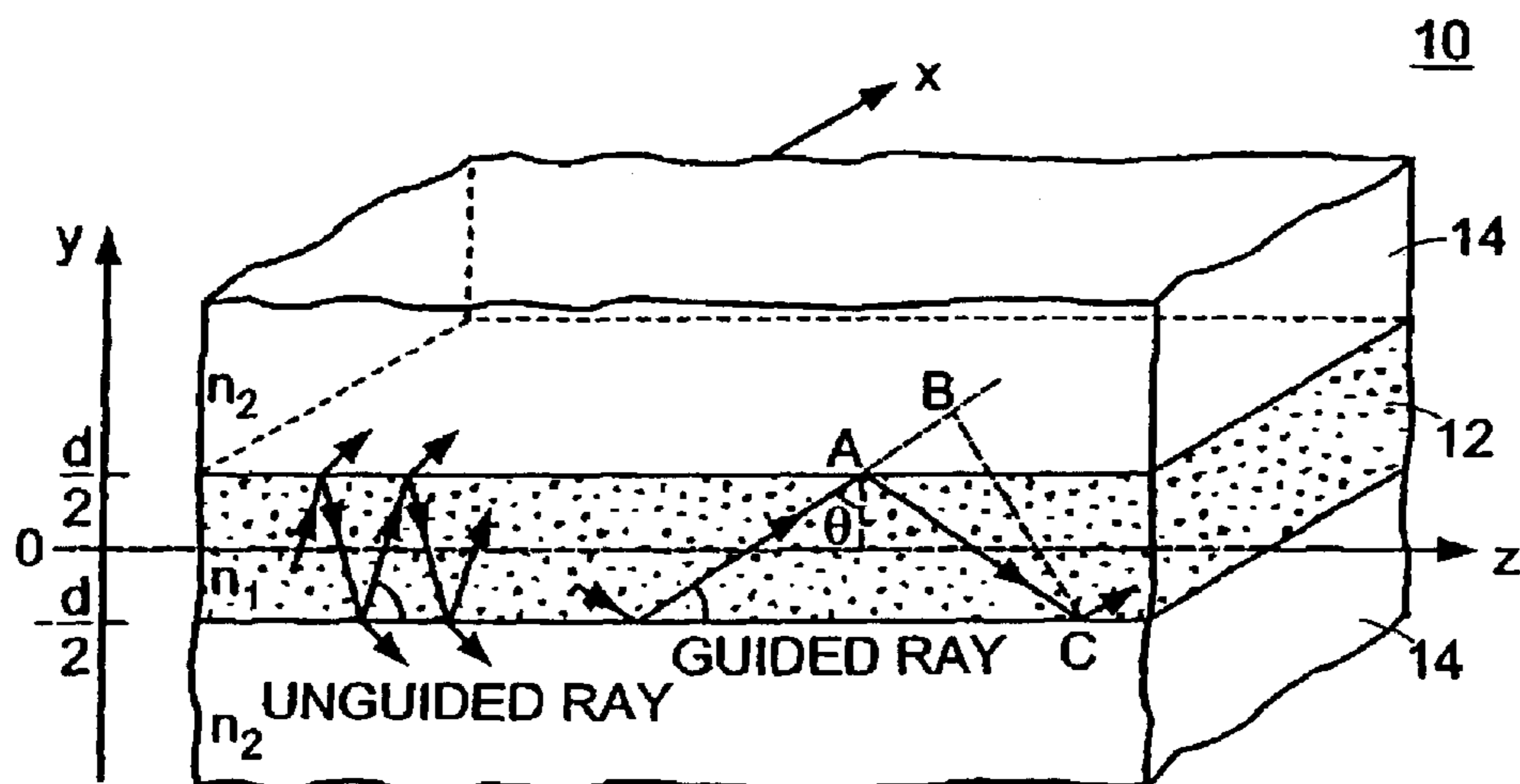


FIG. 1

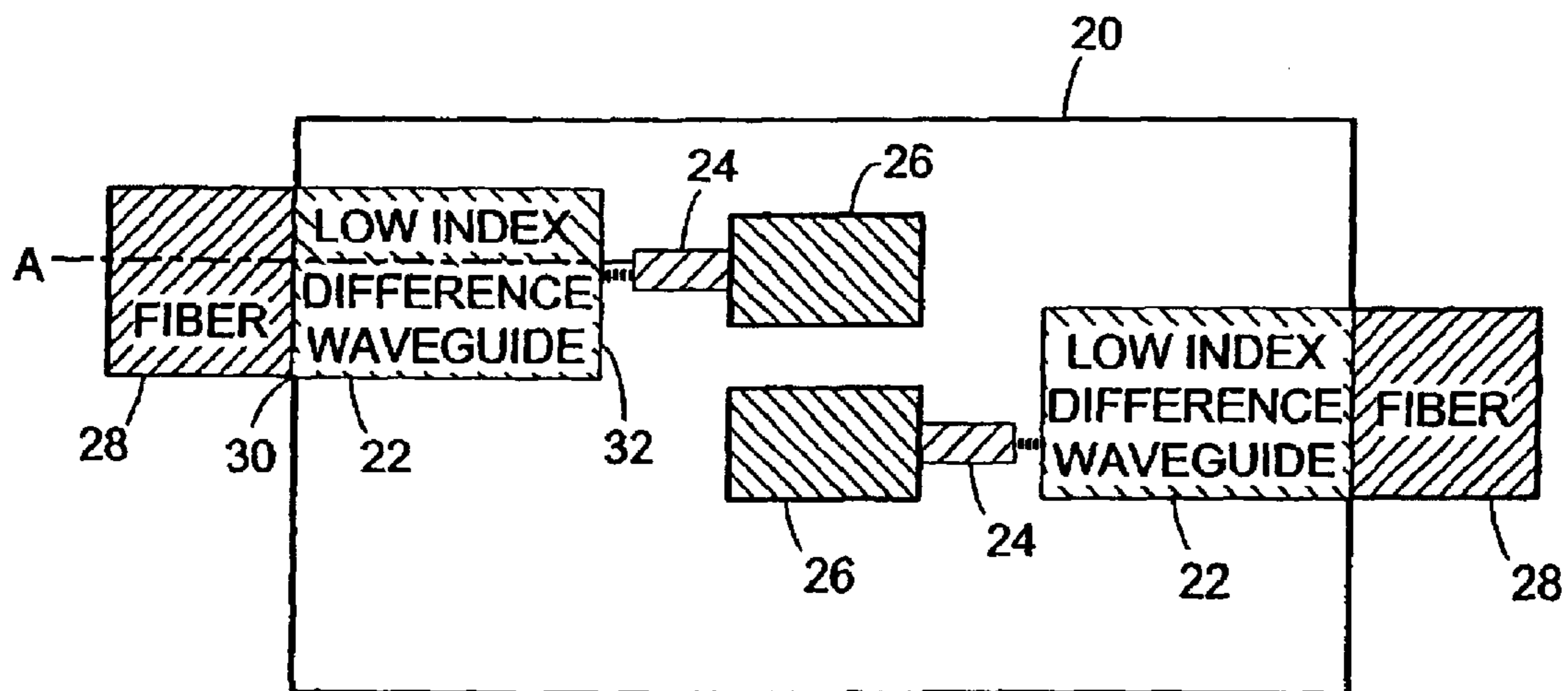


FIG. 2

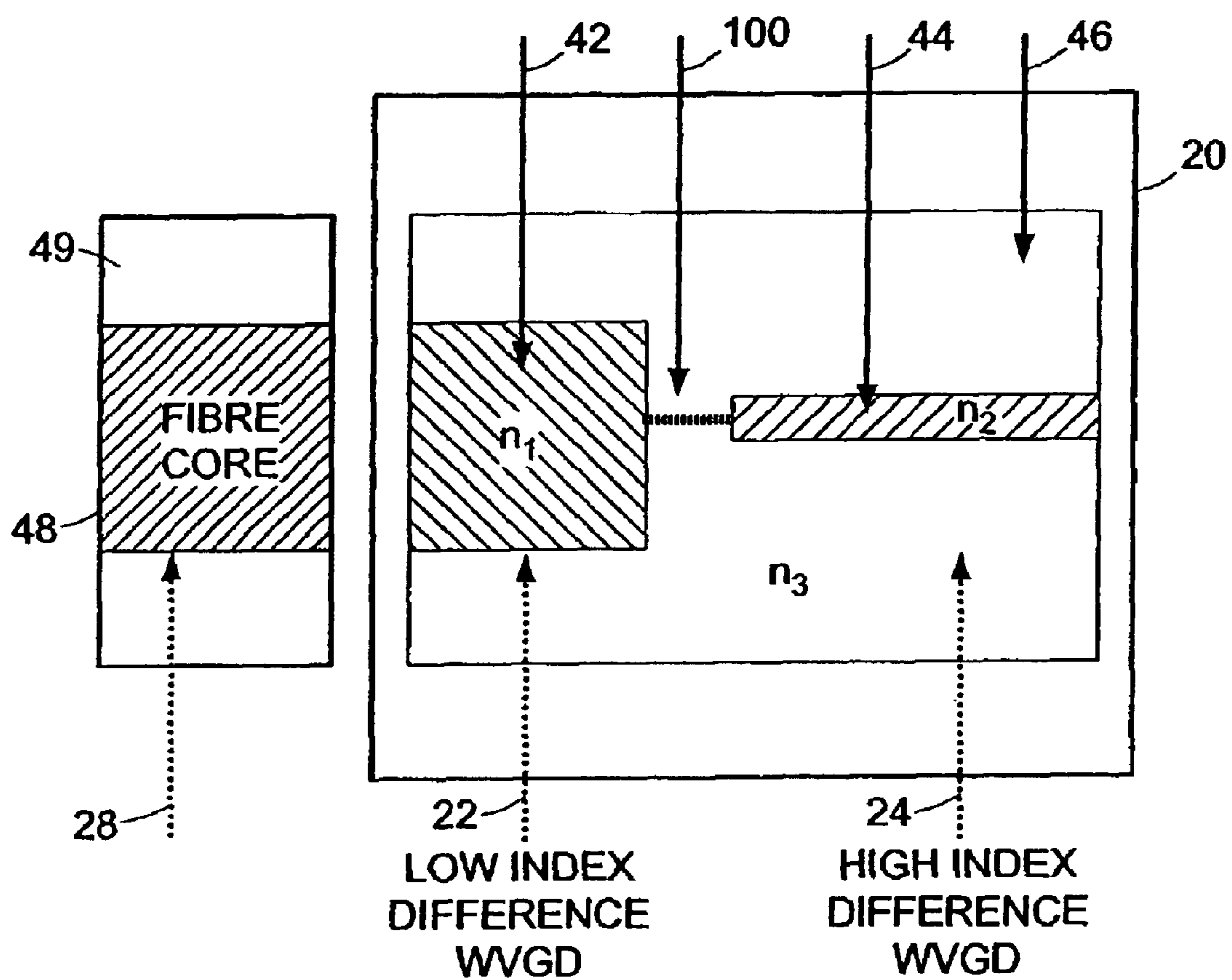


FIG. 3

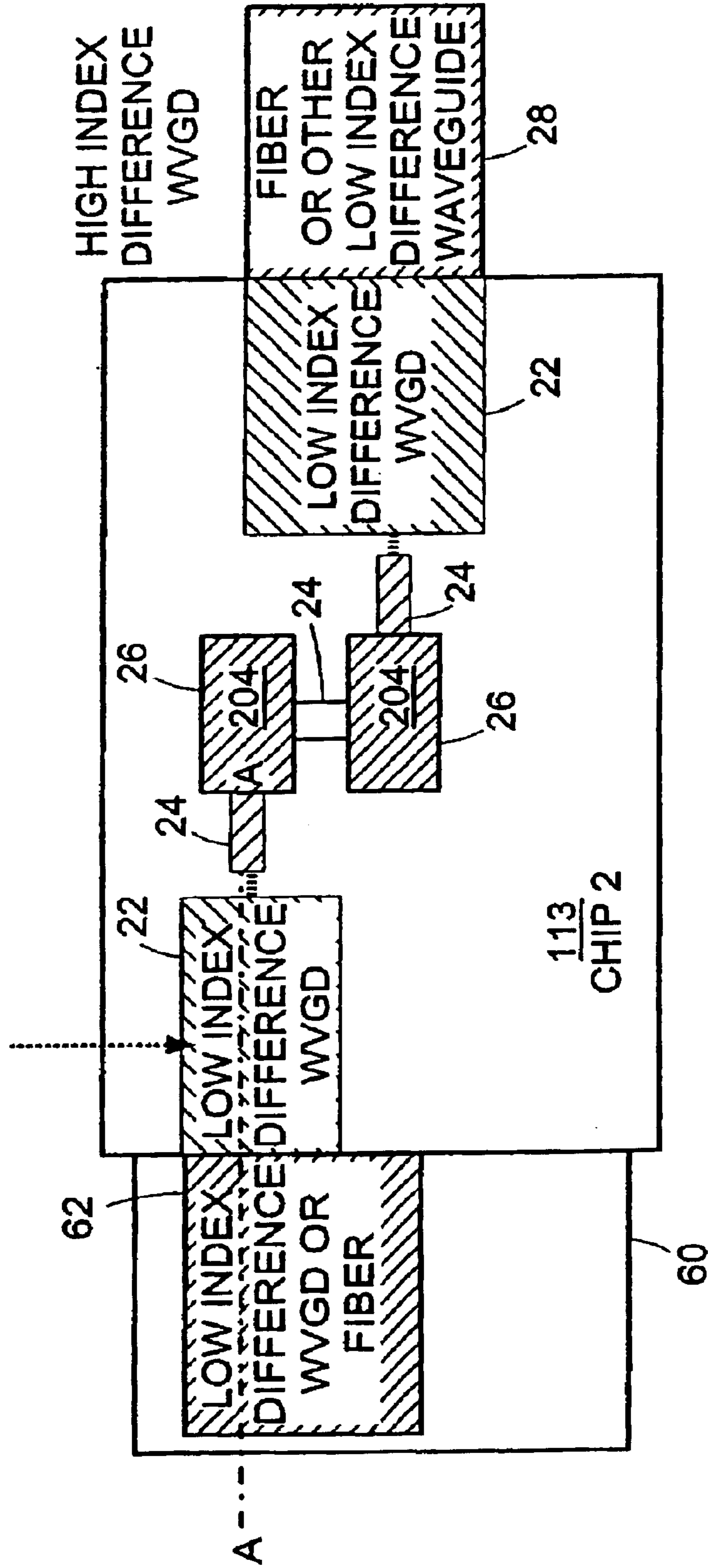


FIG. 4

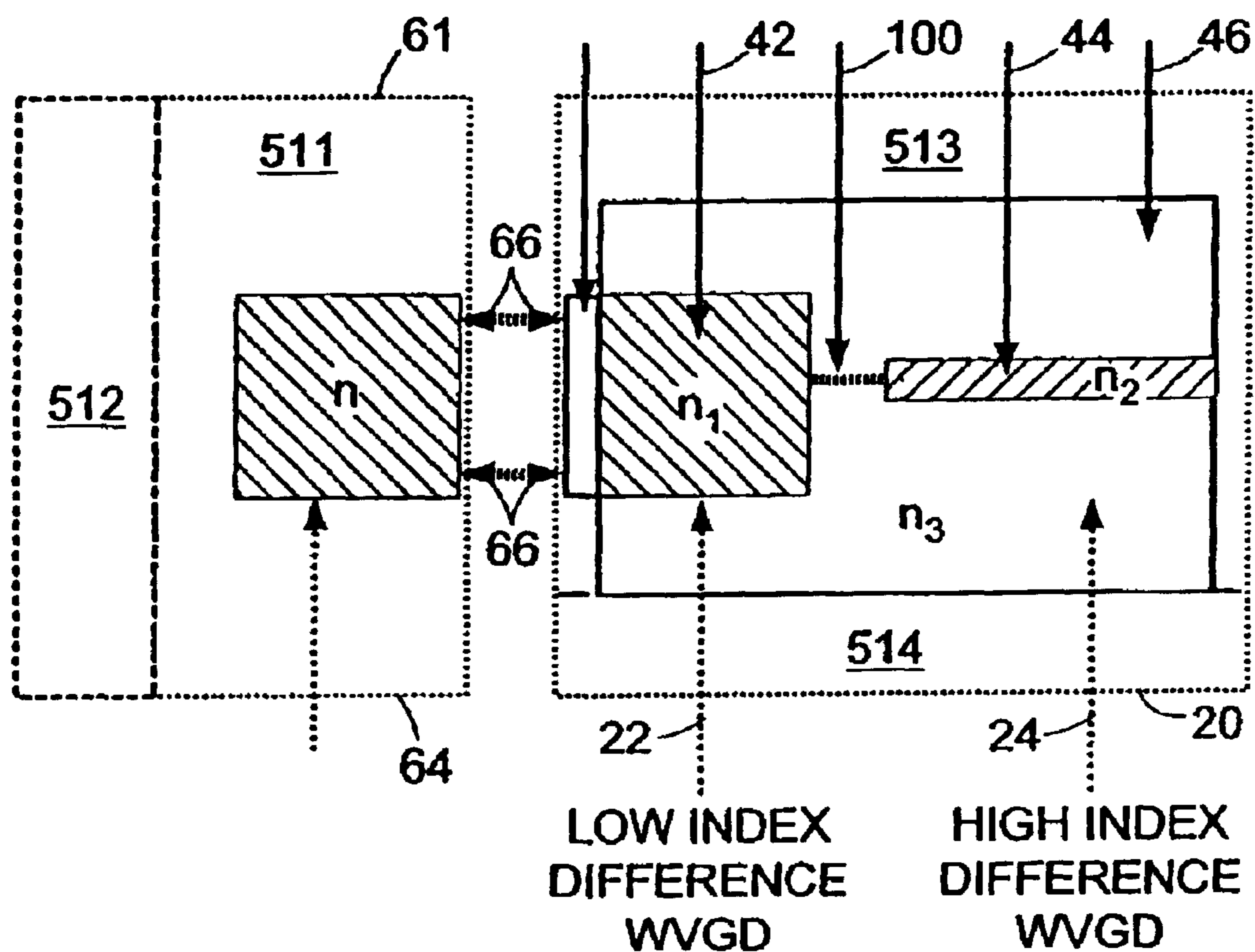


FIG. 5

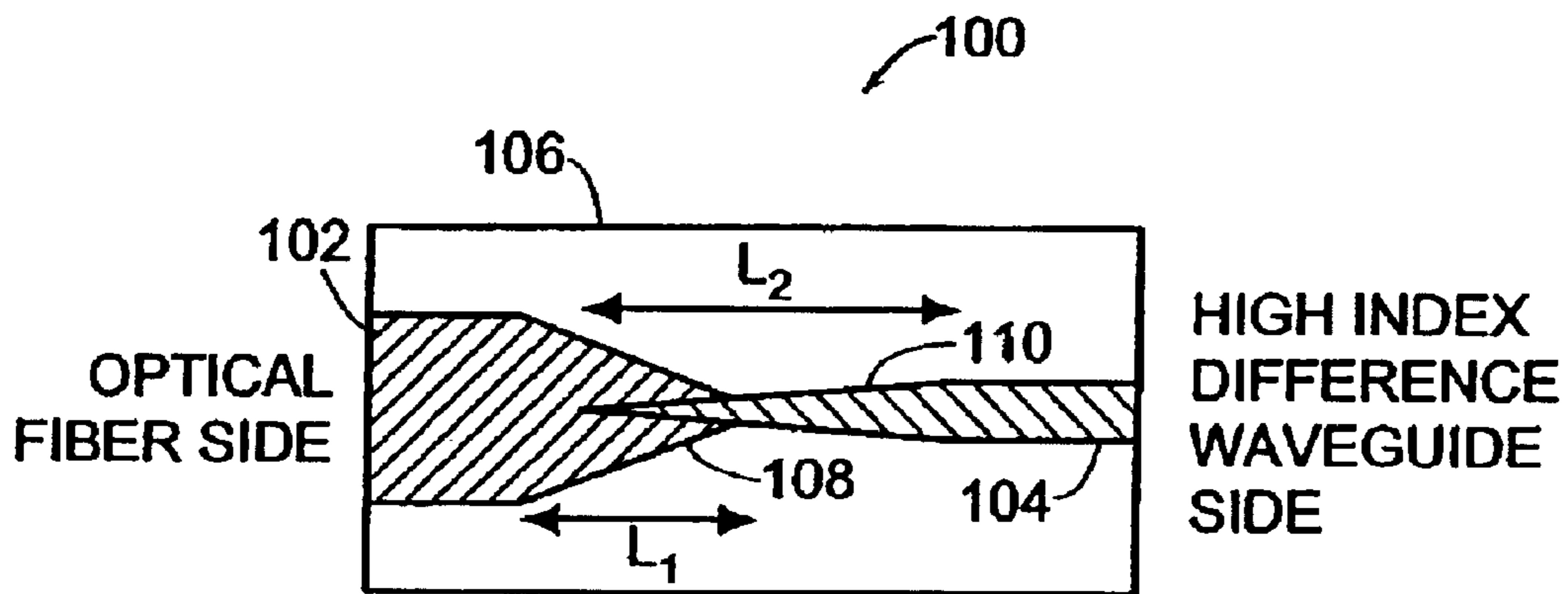


FIG. 6

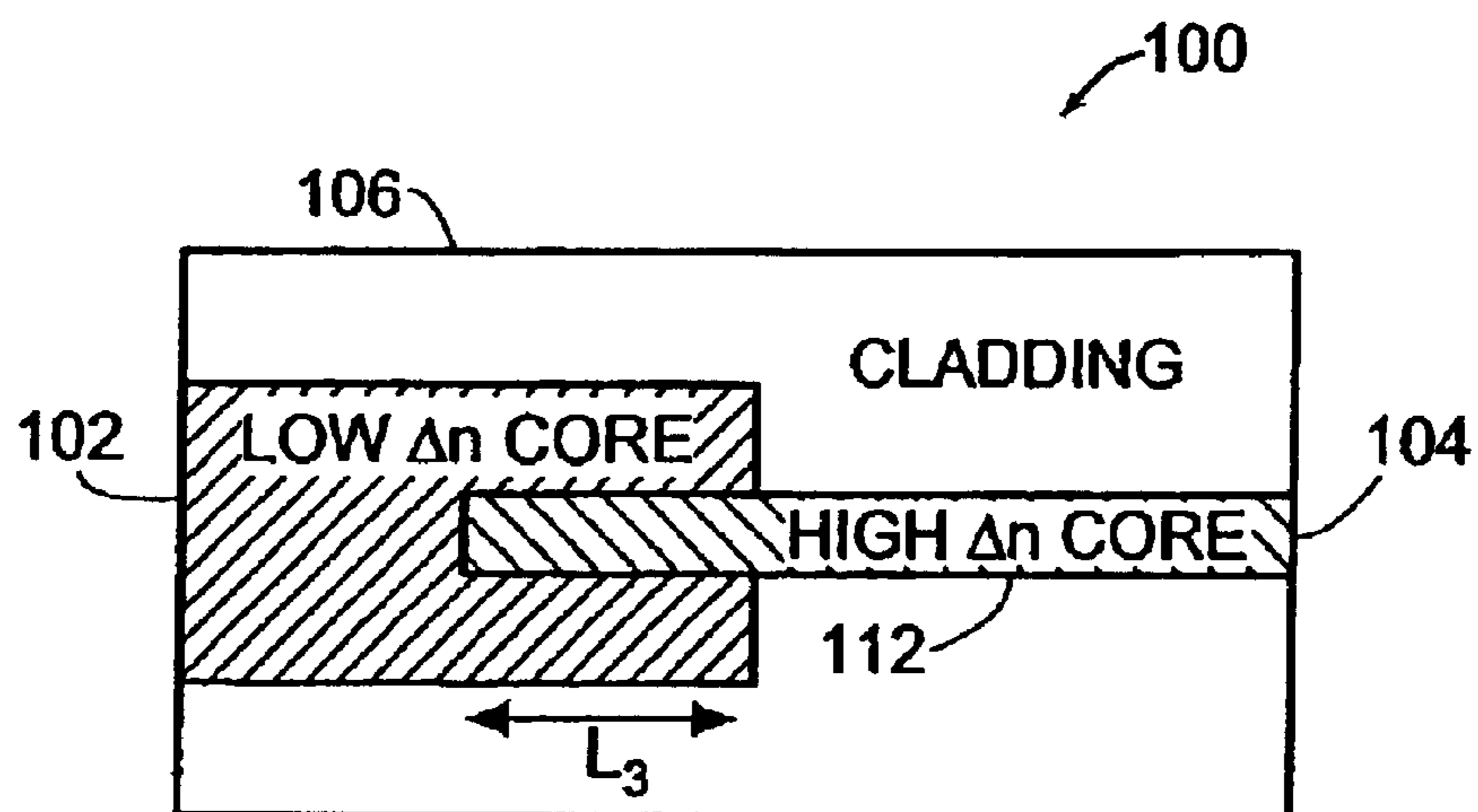


FIG. 7

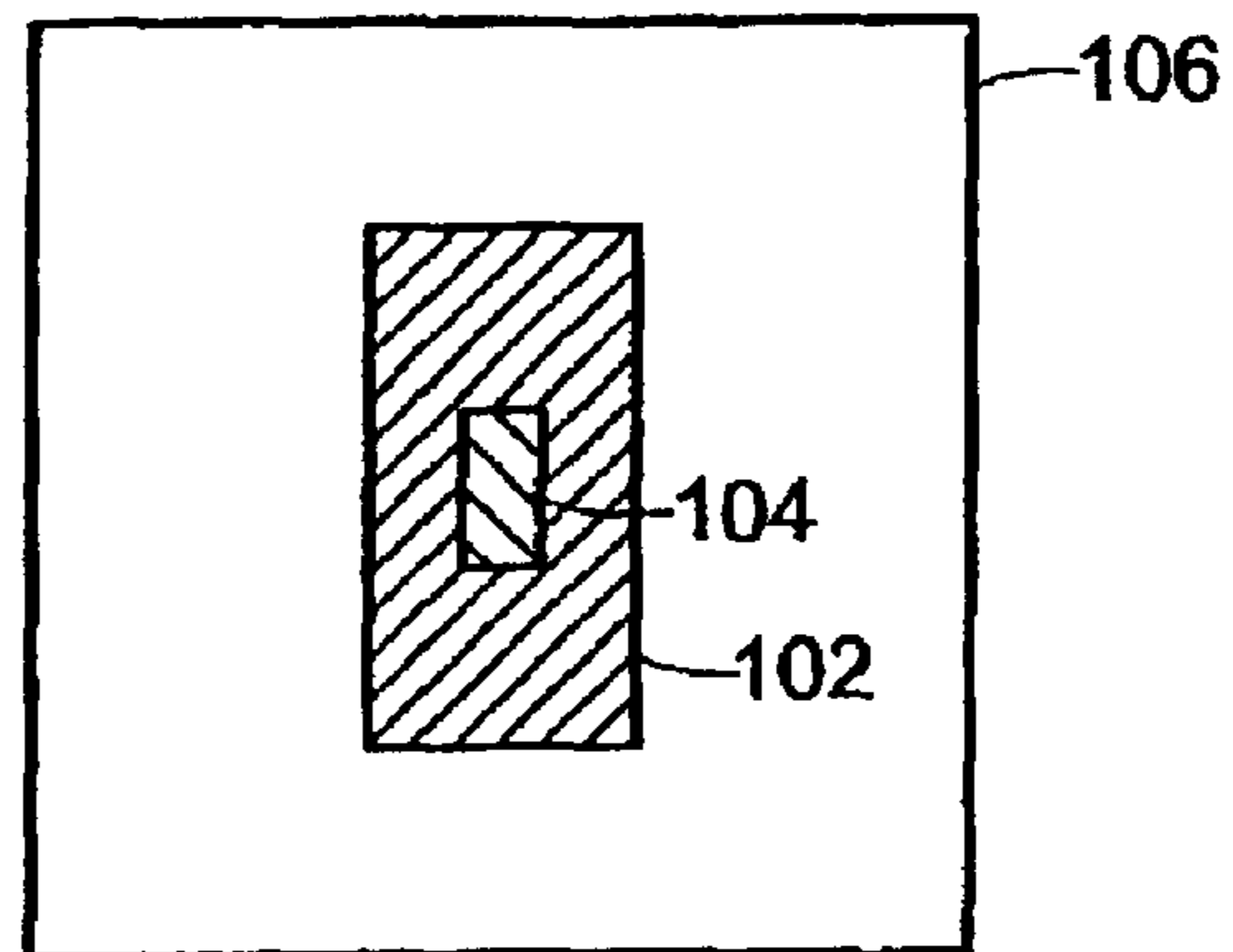


FIG. 8

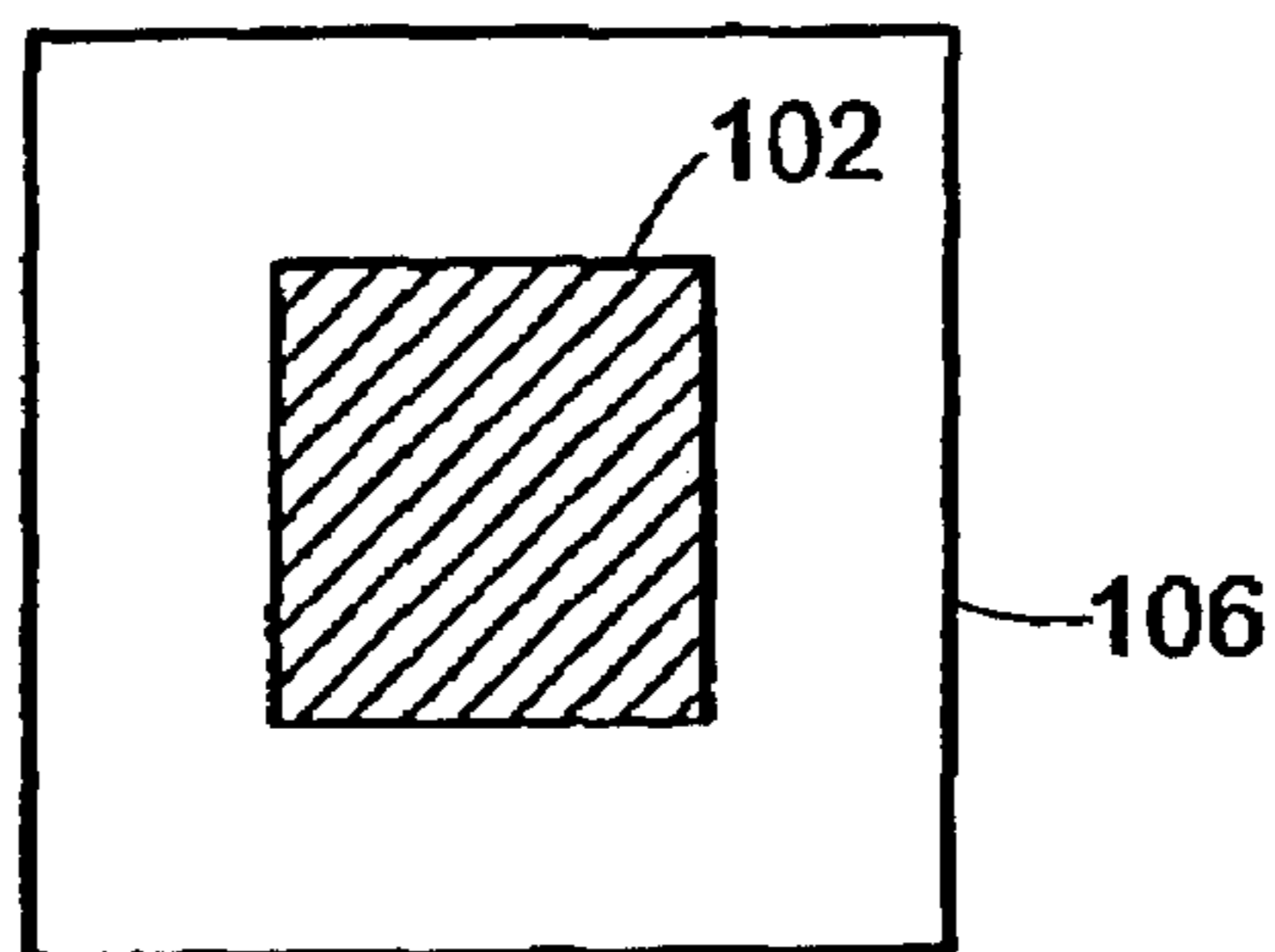


FIG. 9

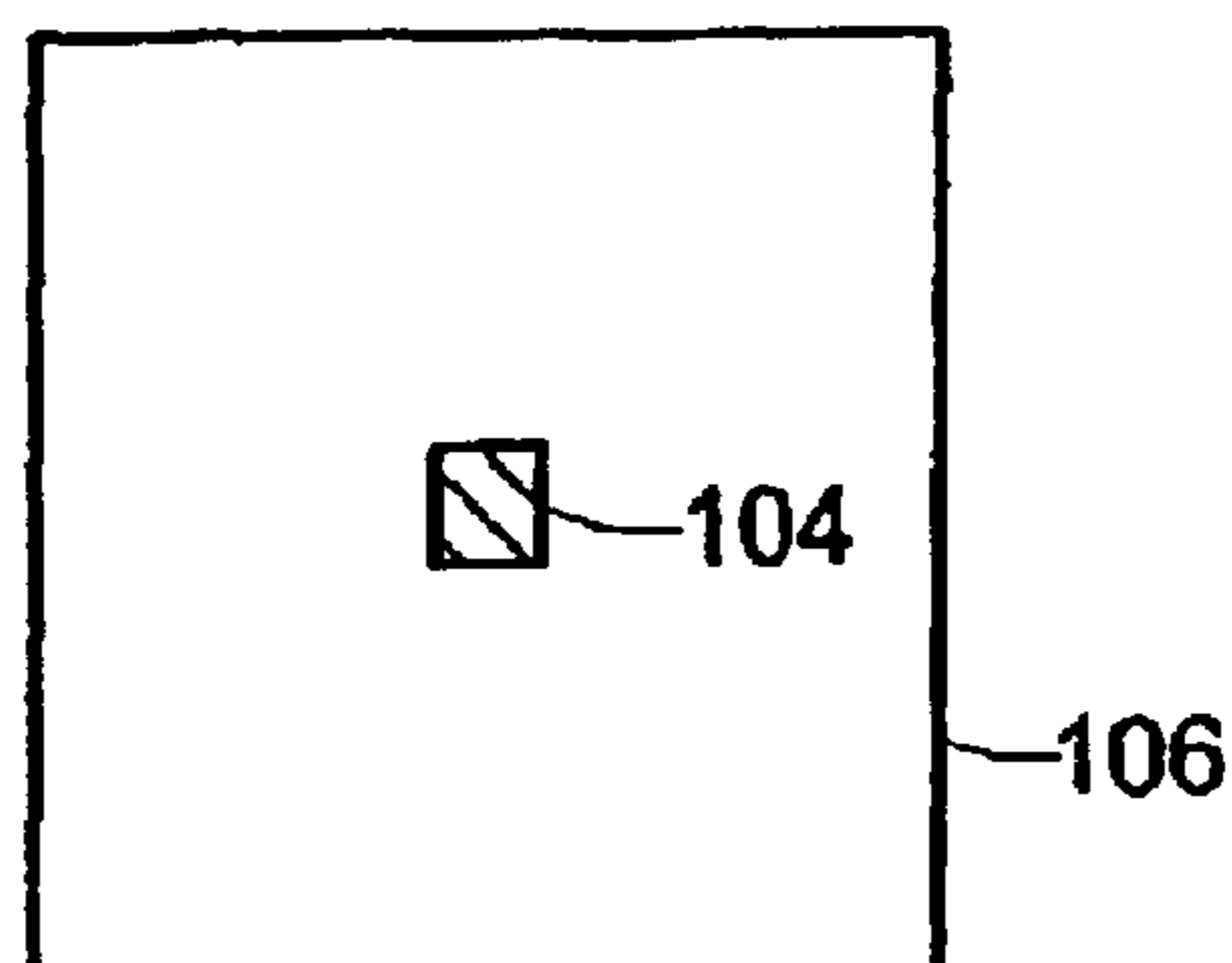


FIG. 10

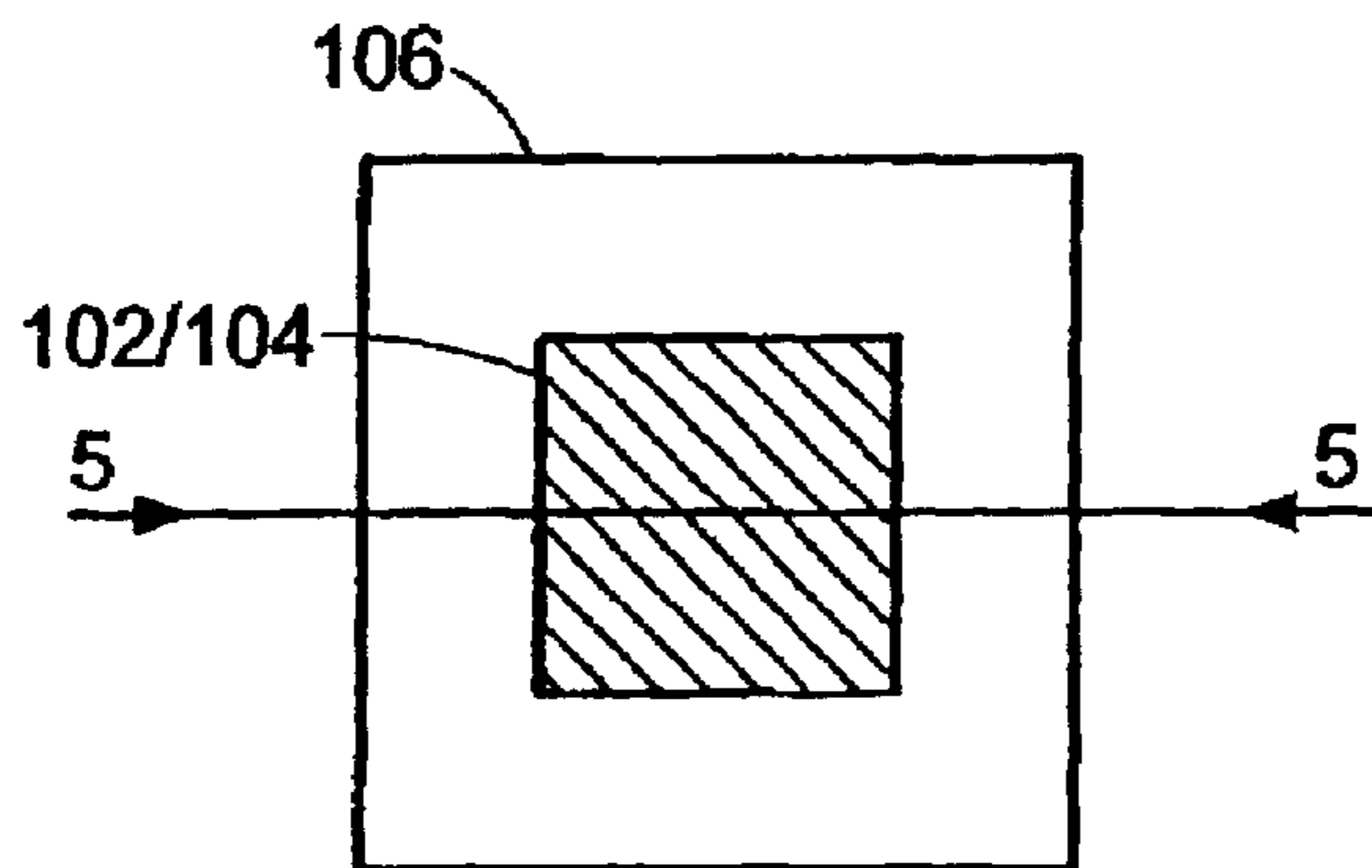


FIG. 11A

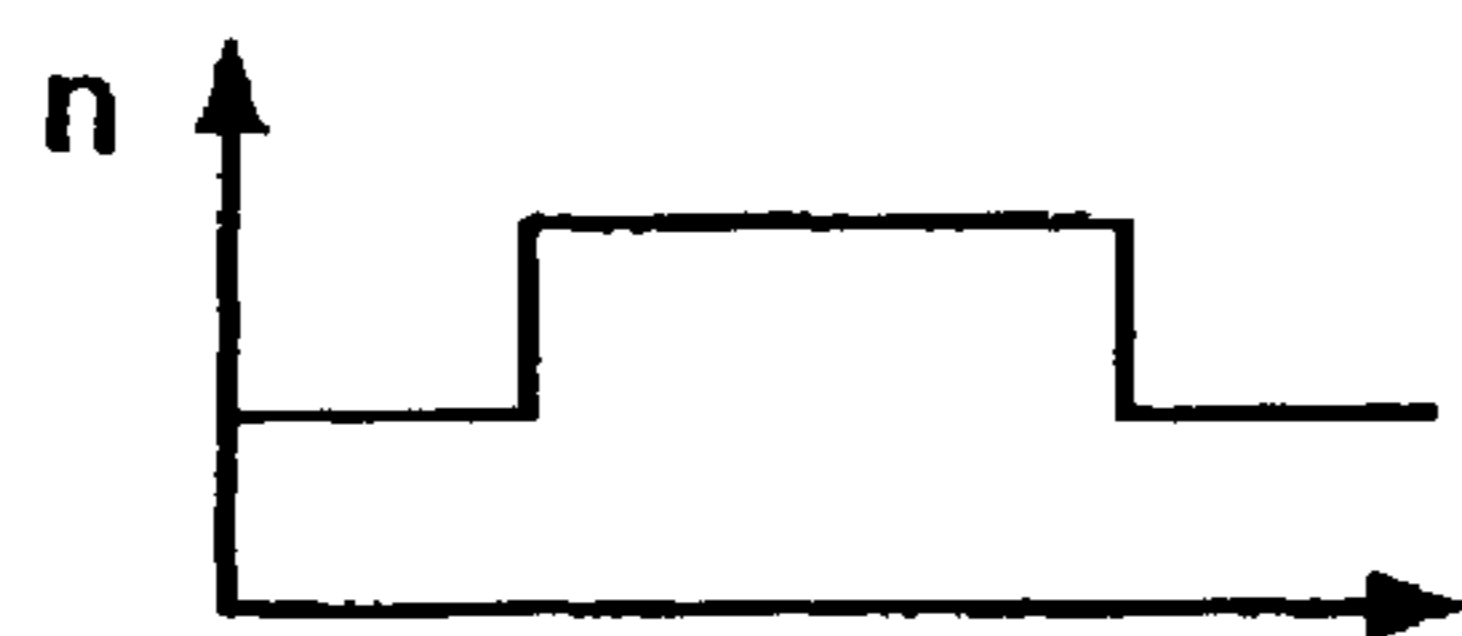


FIG. 11B

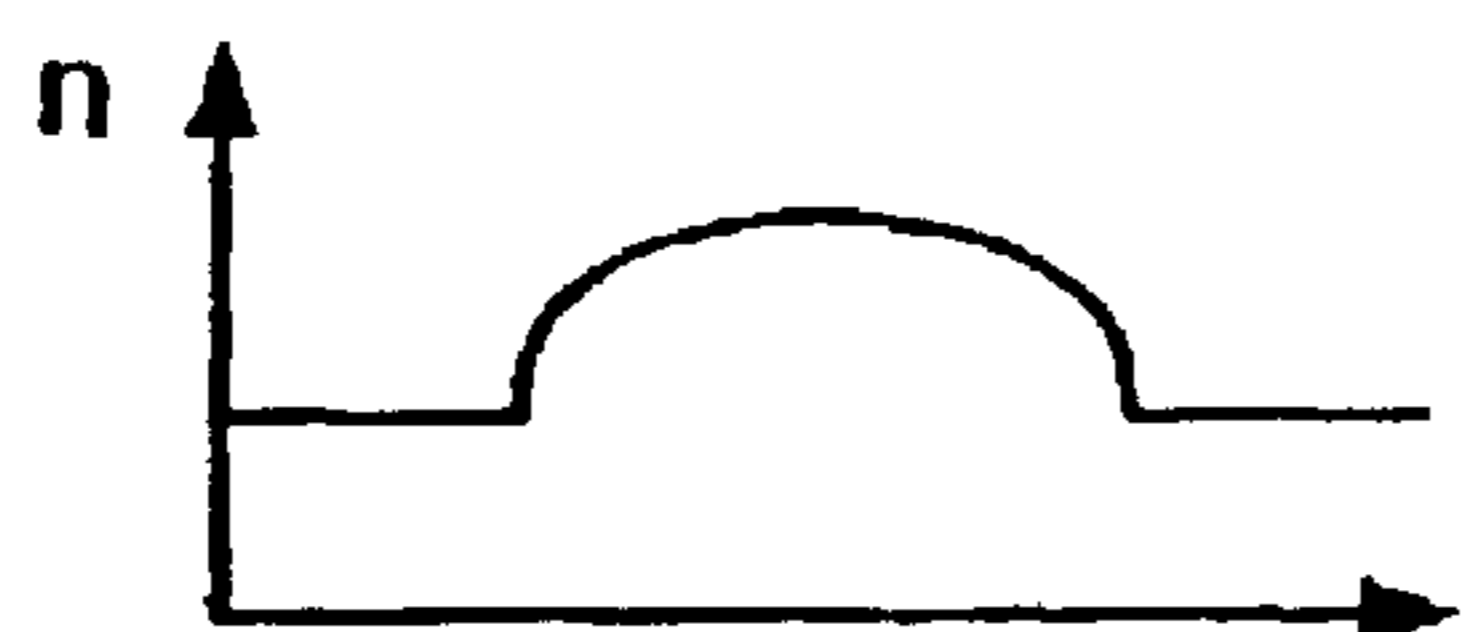


FIG. 11C



FIG. 11D



FIG. 11E



FIG. 11F

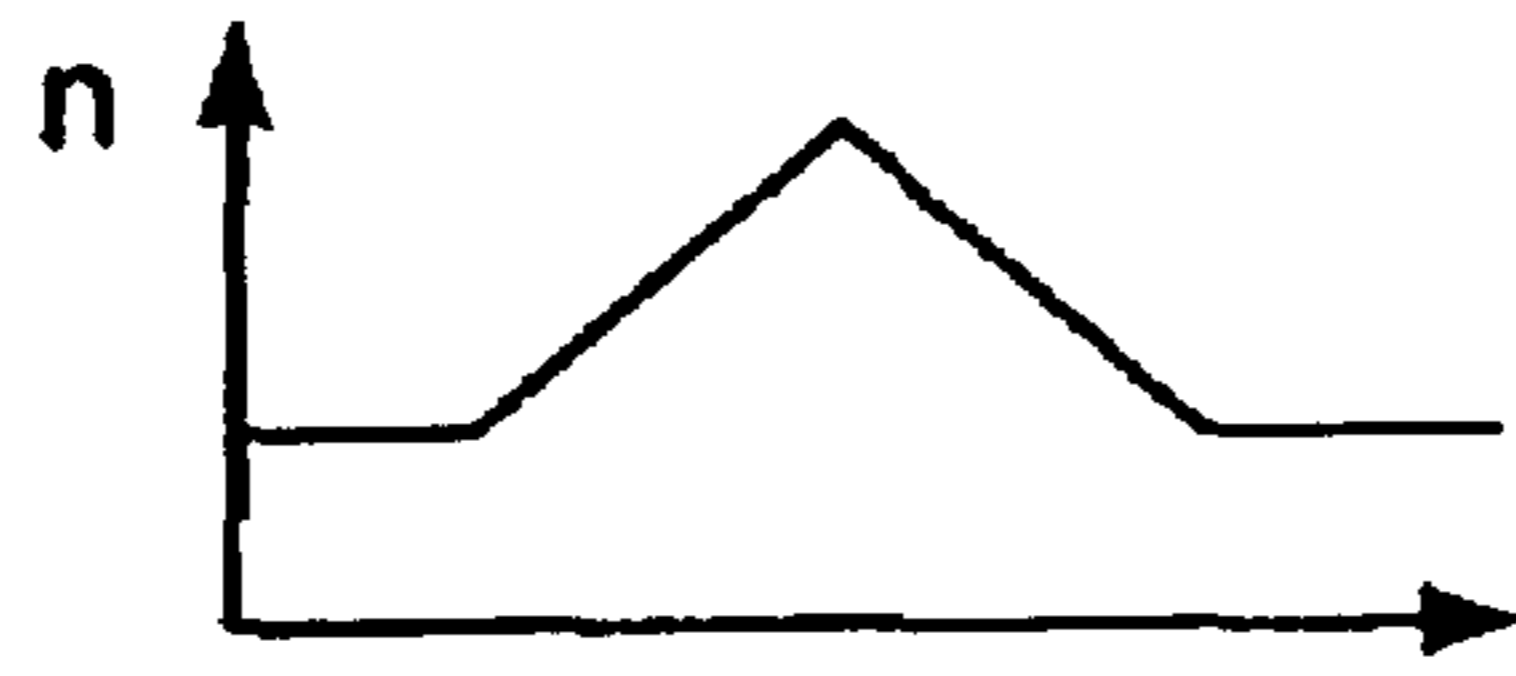


FIG. 11G

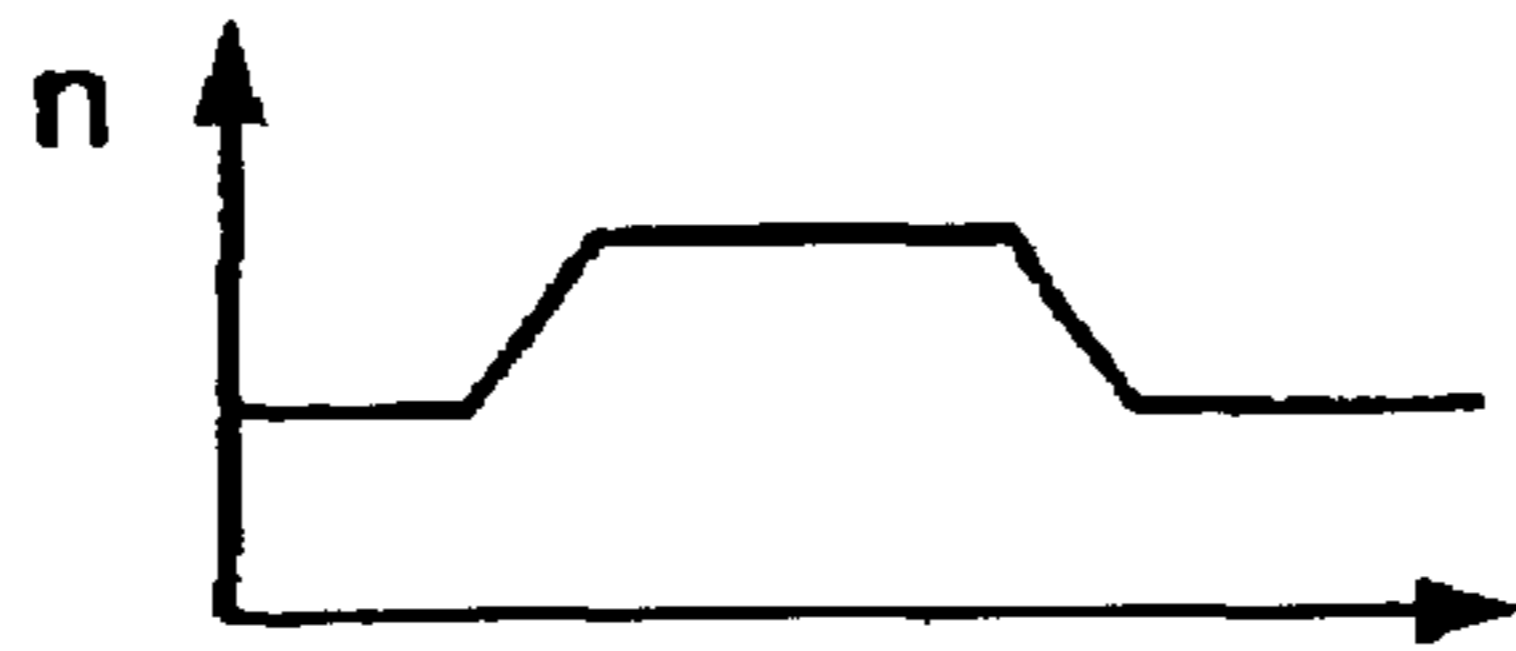


FIG. 11H

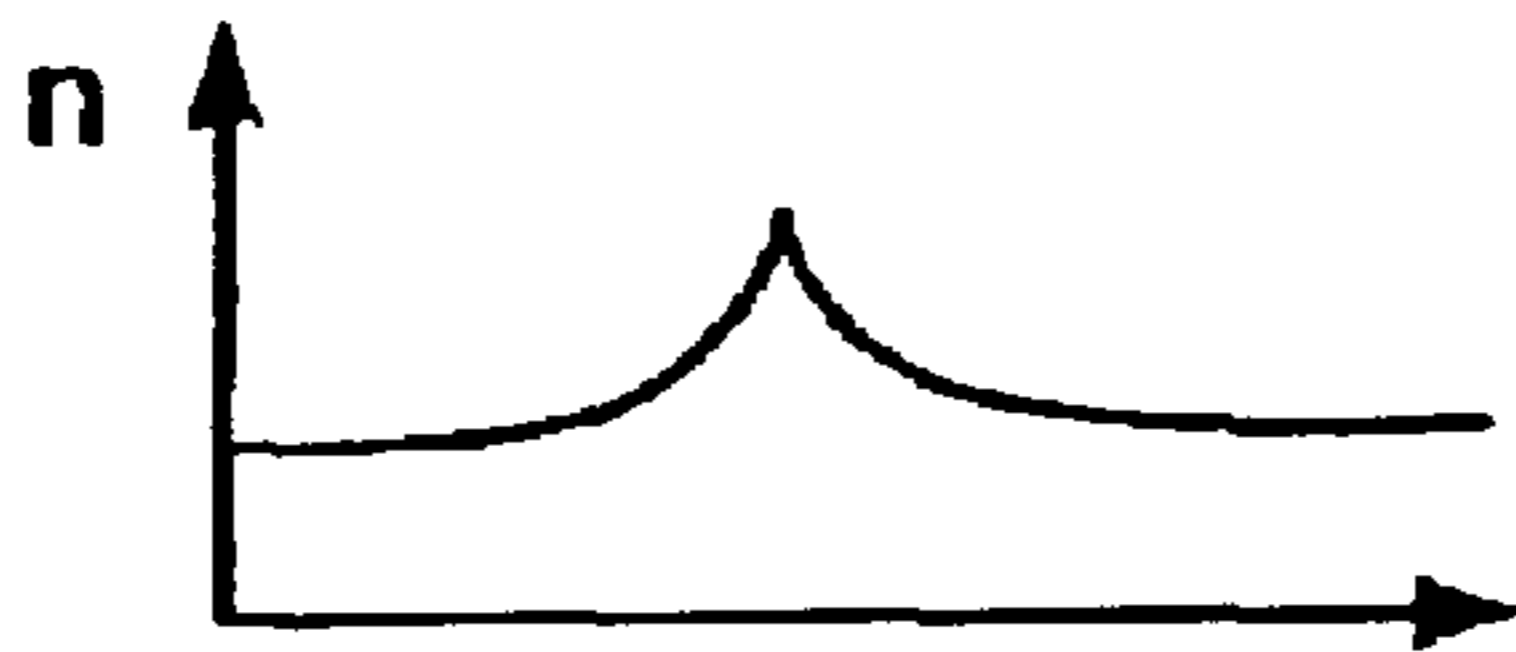


FIG. 11I

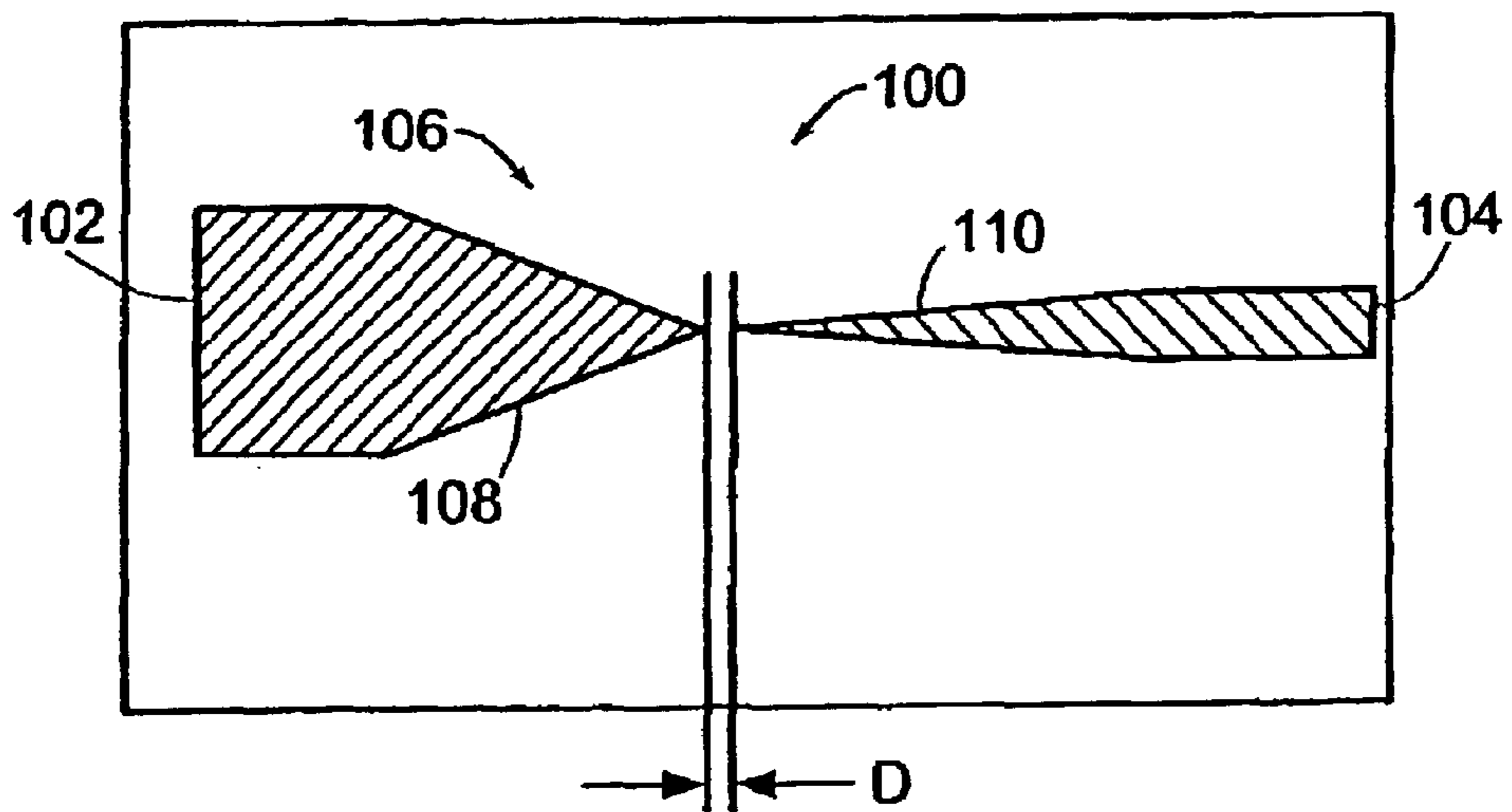


FIG. 12

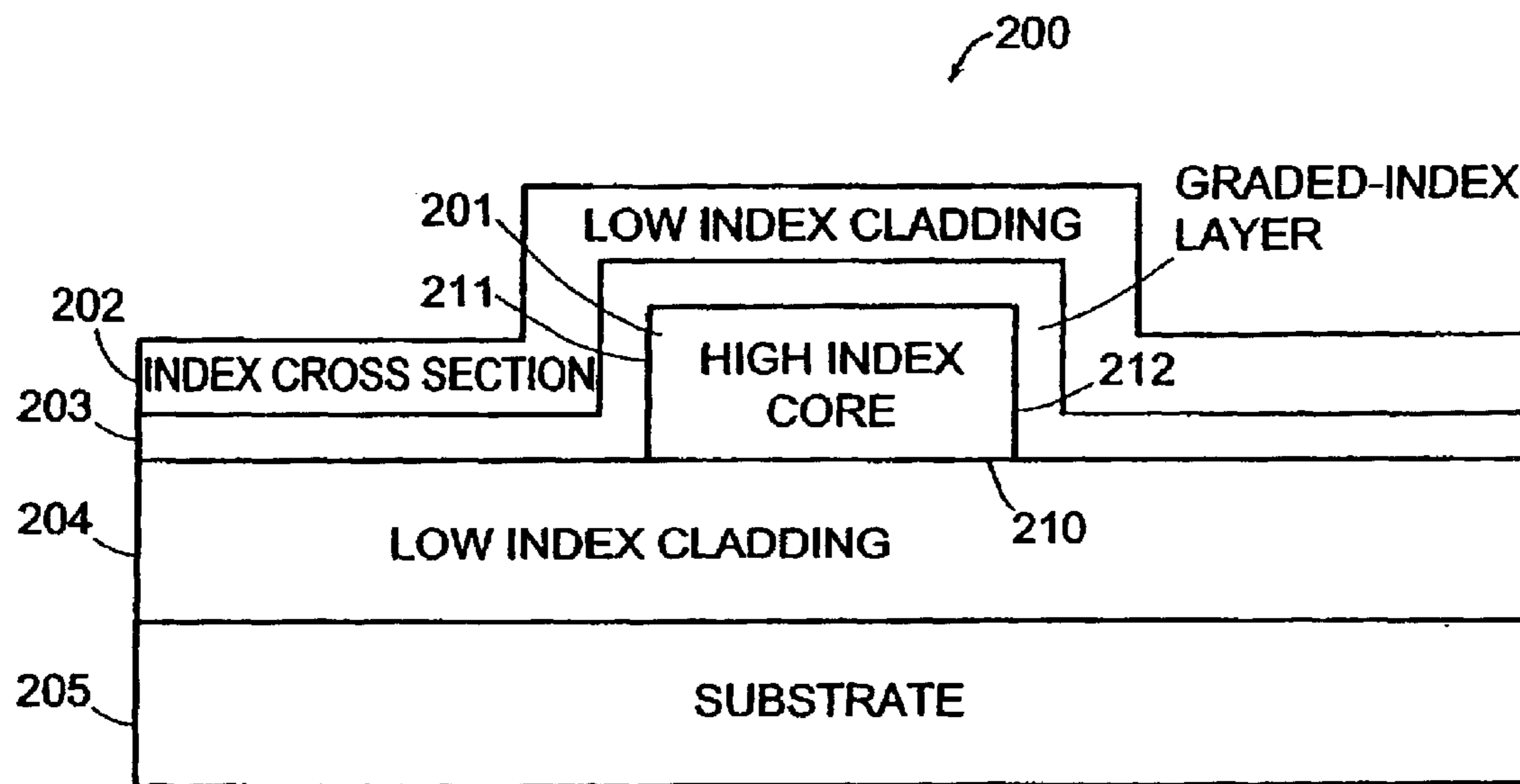


FIG. 13

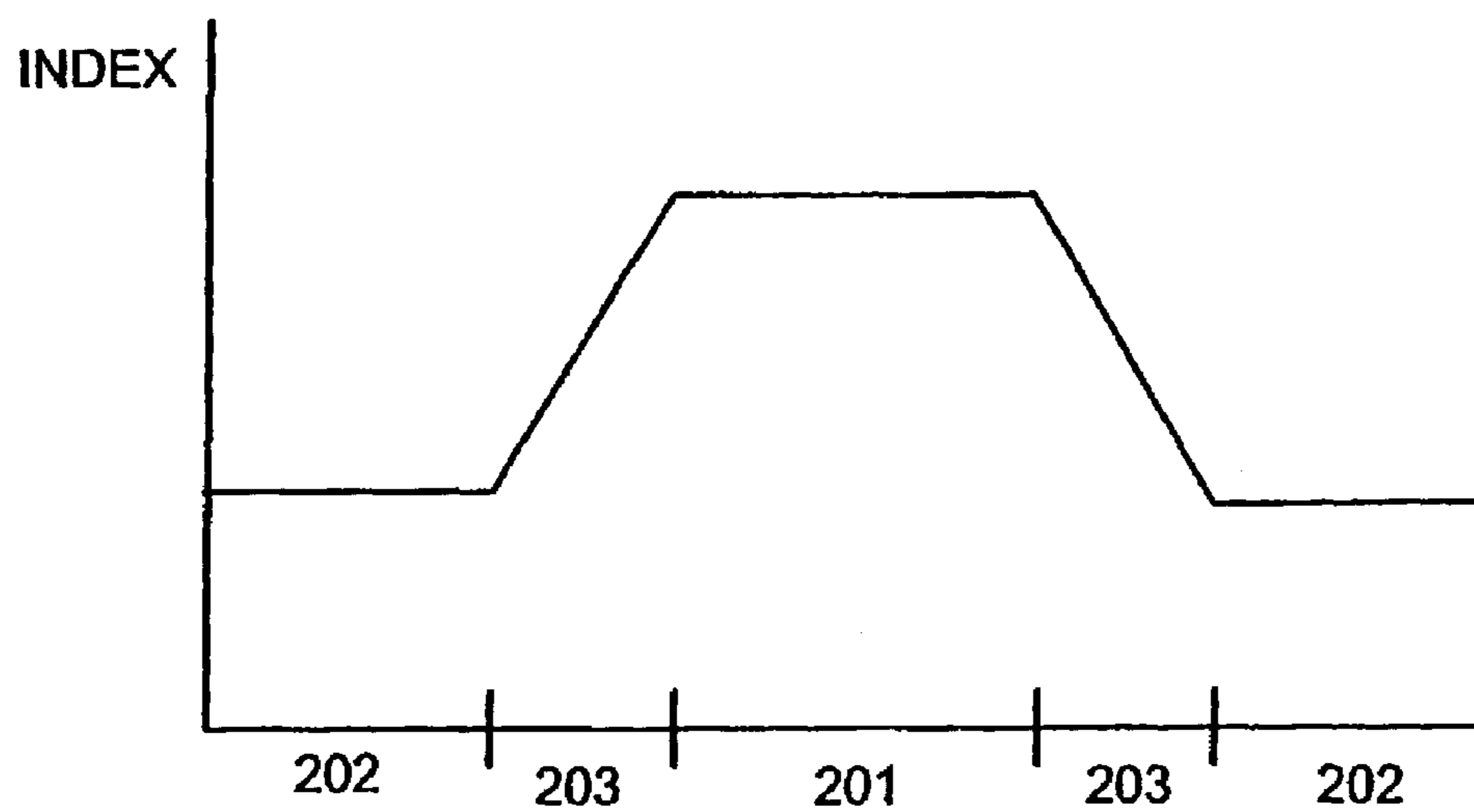


FIG. 14

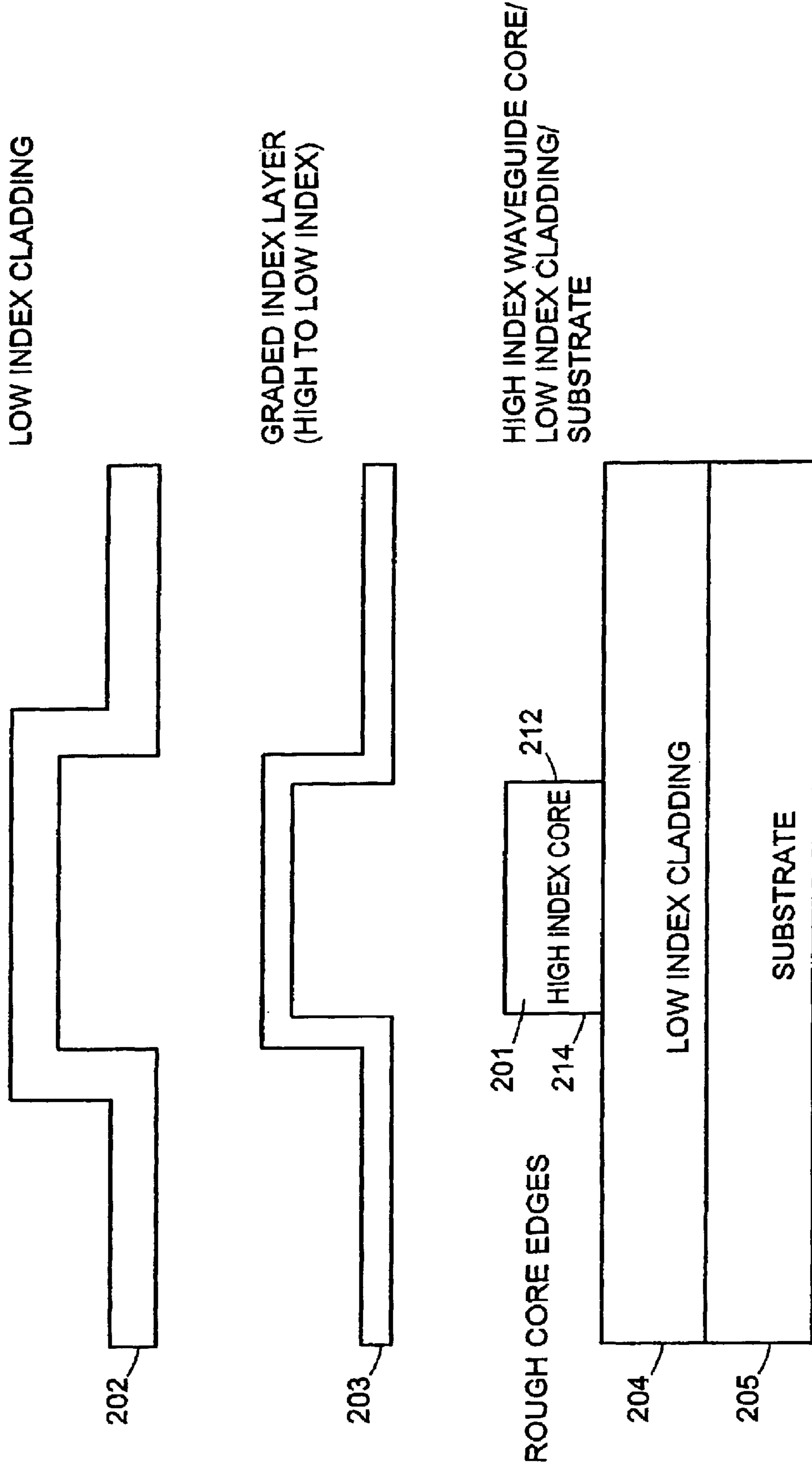


FIG. 15

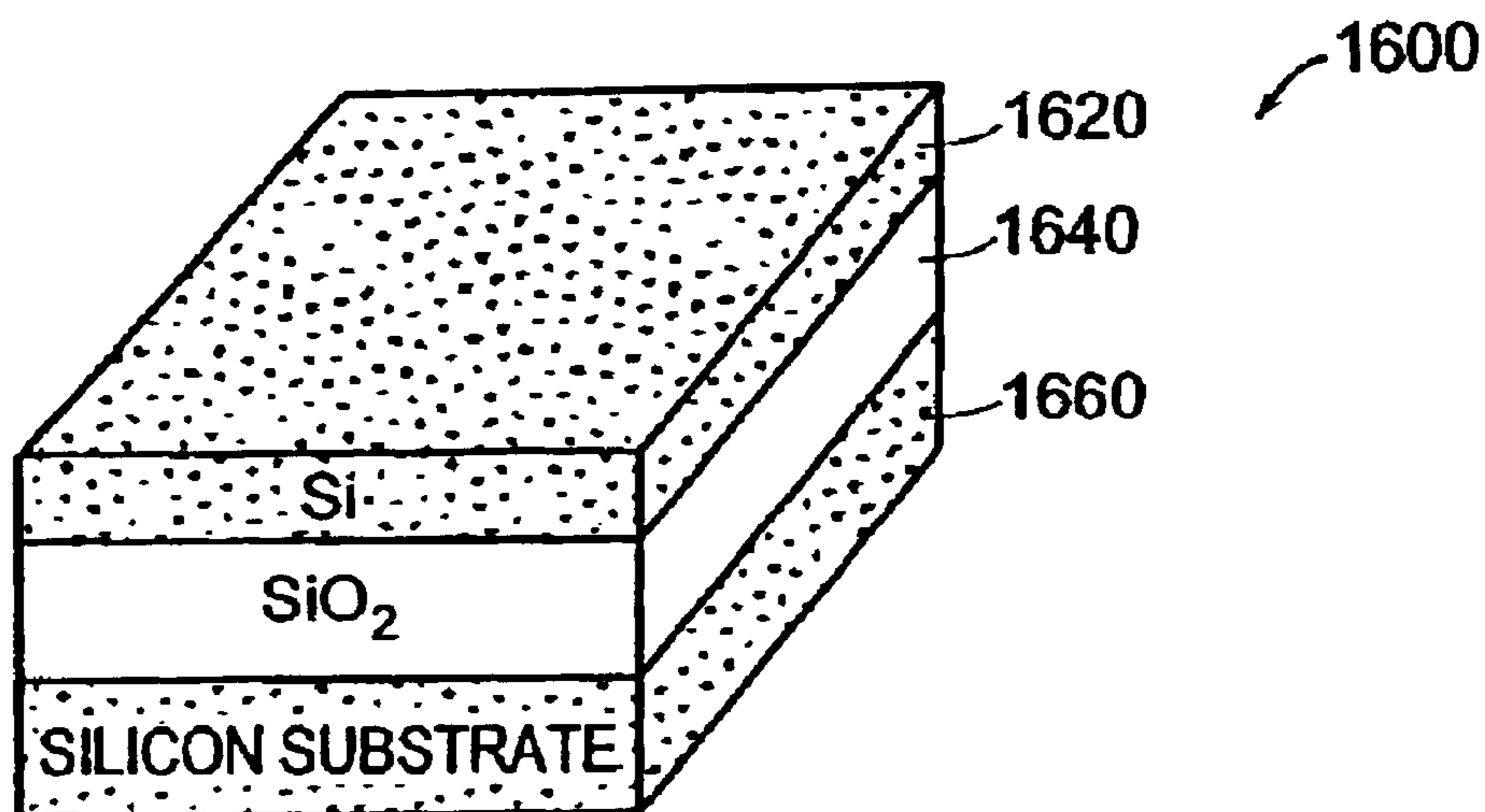


FIG. 16

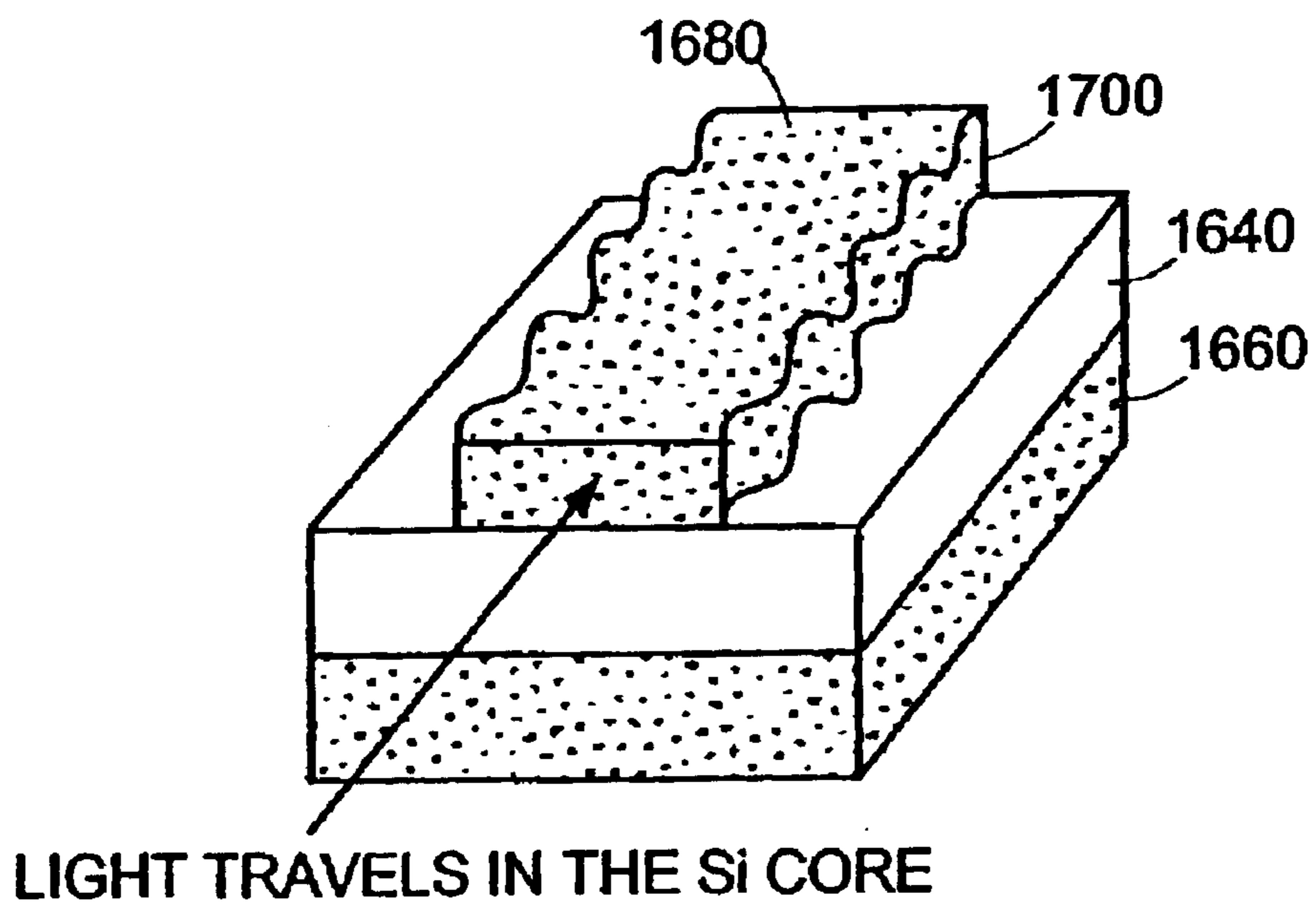


FIG. 17

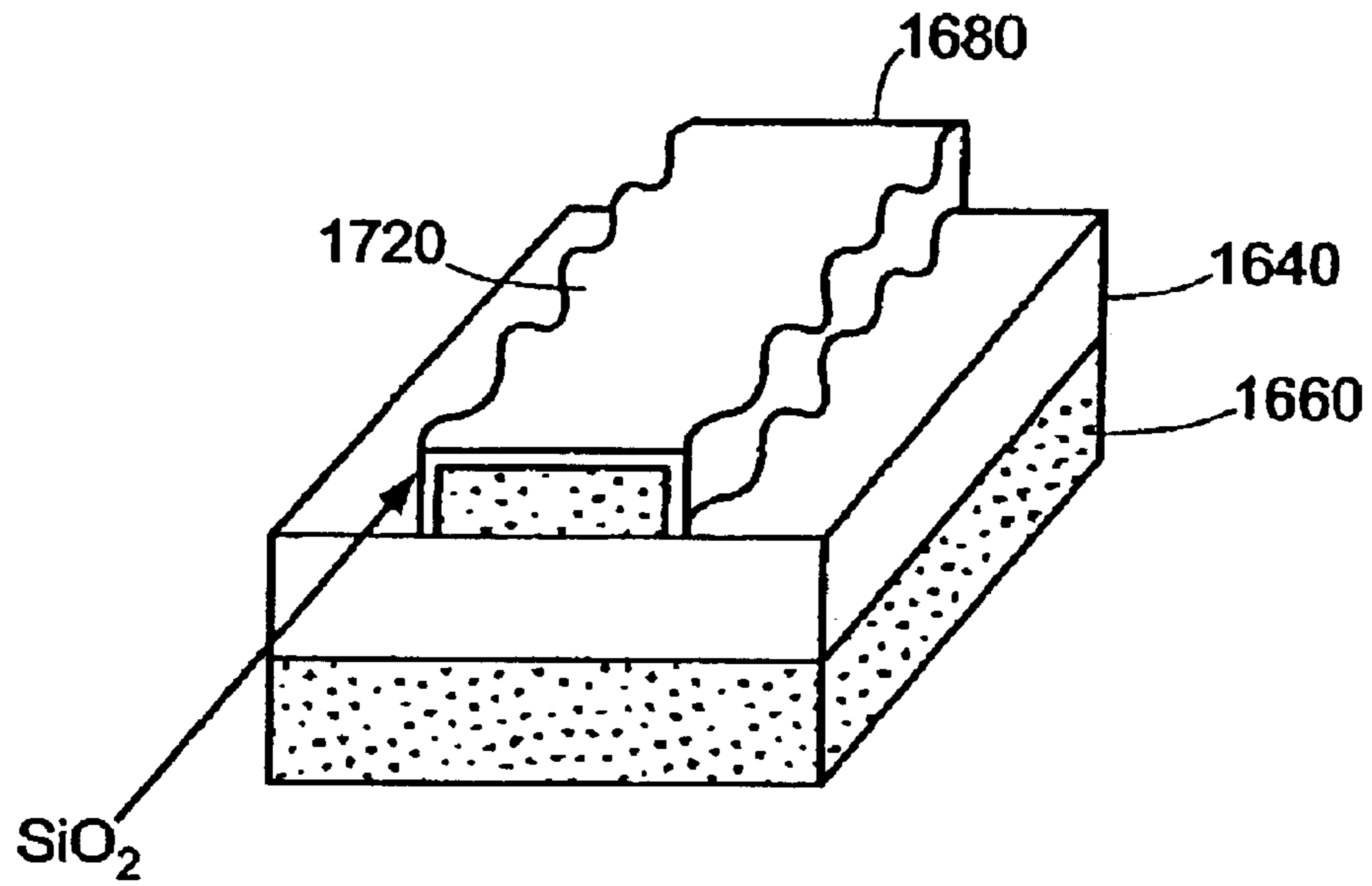


FIG. 18

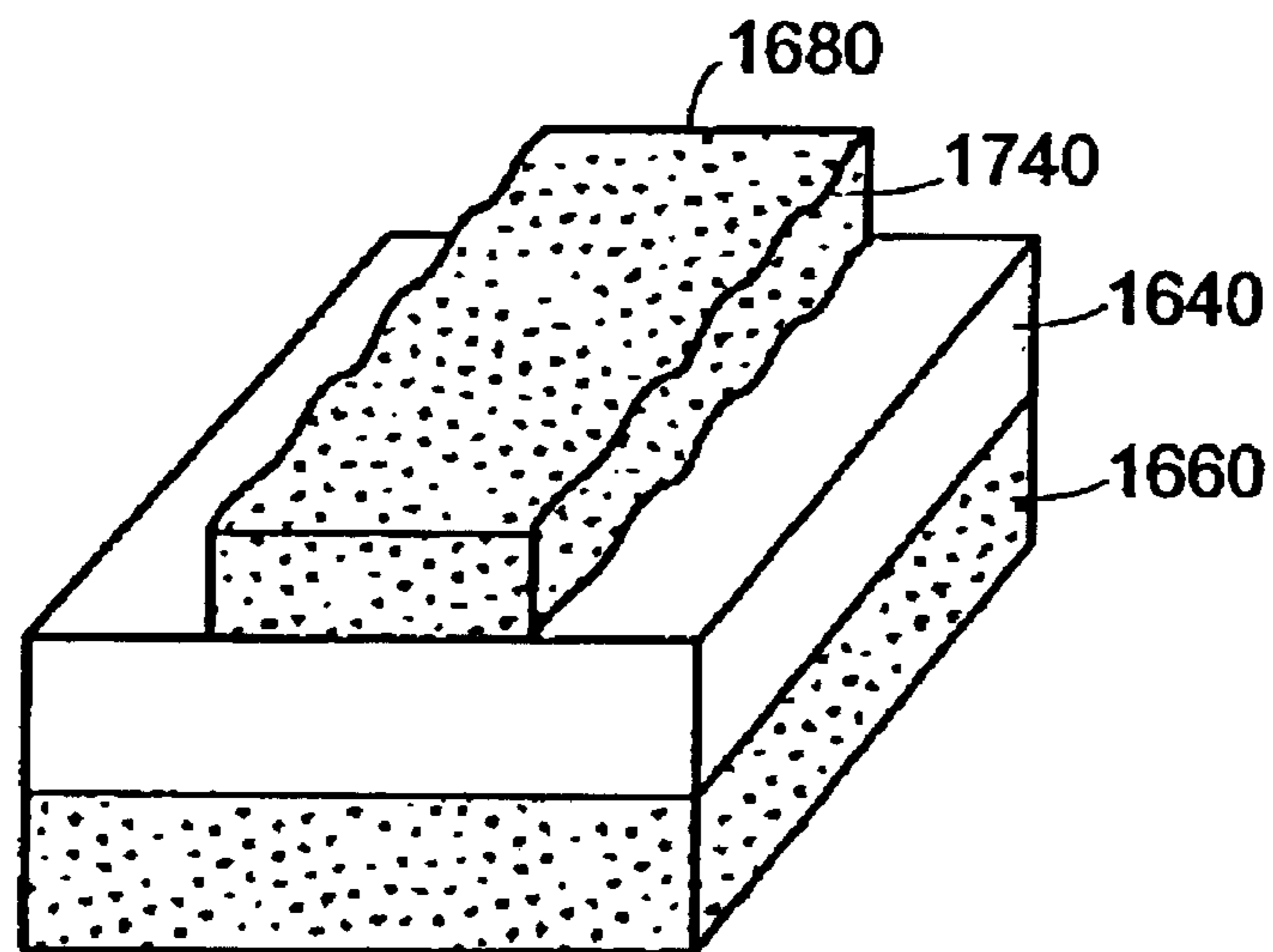


FIG. 19

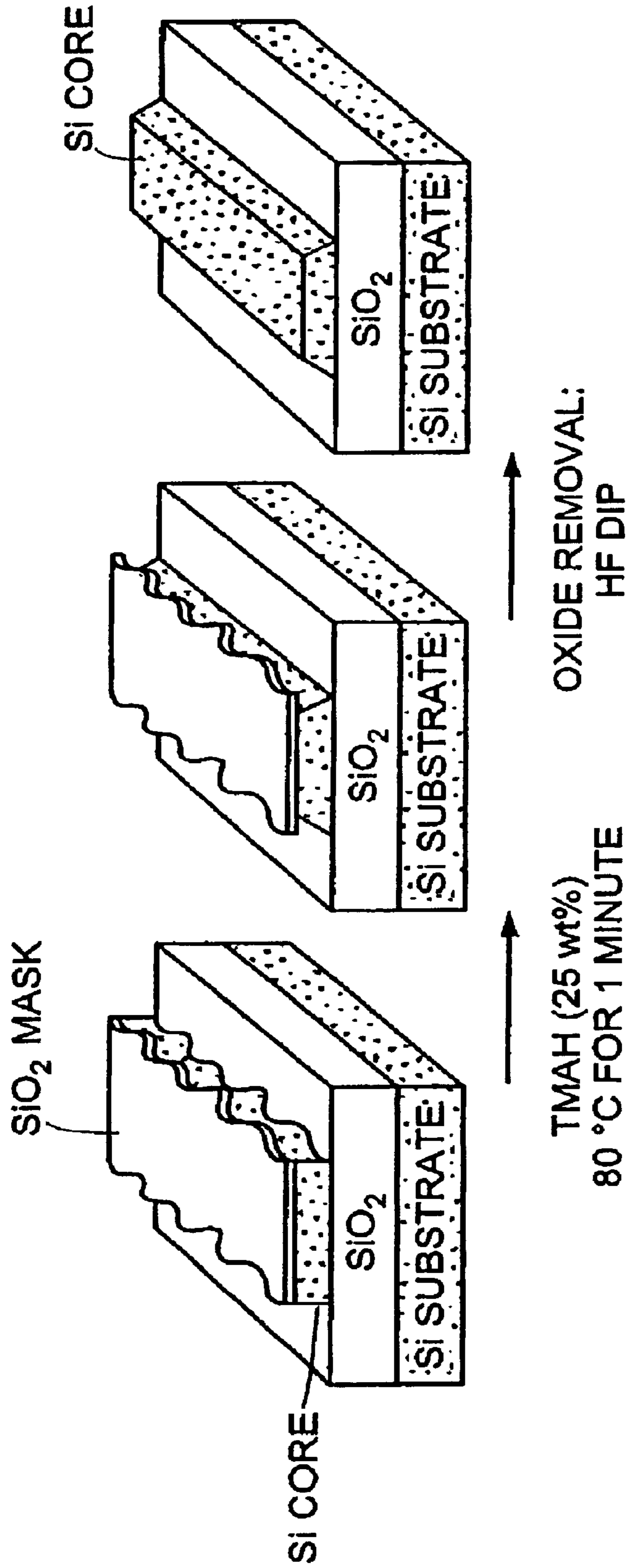


FIG. 20

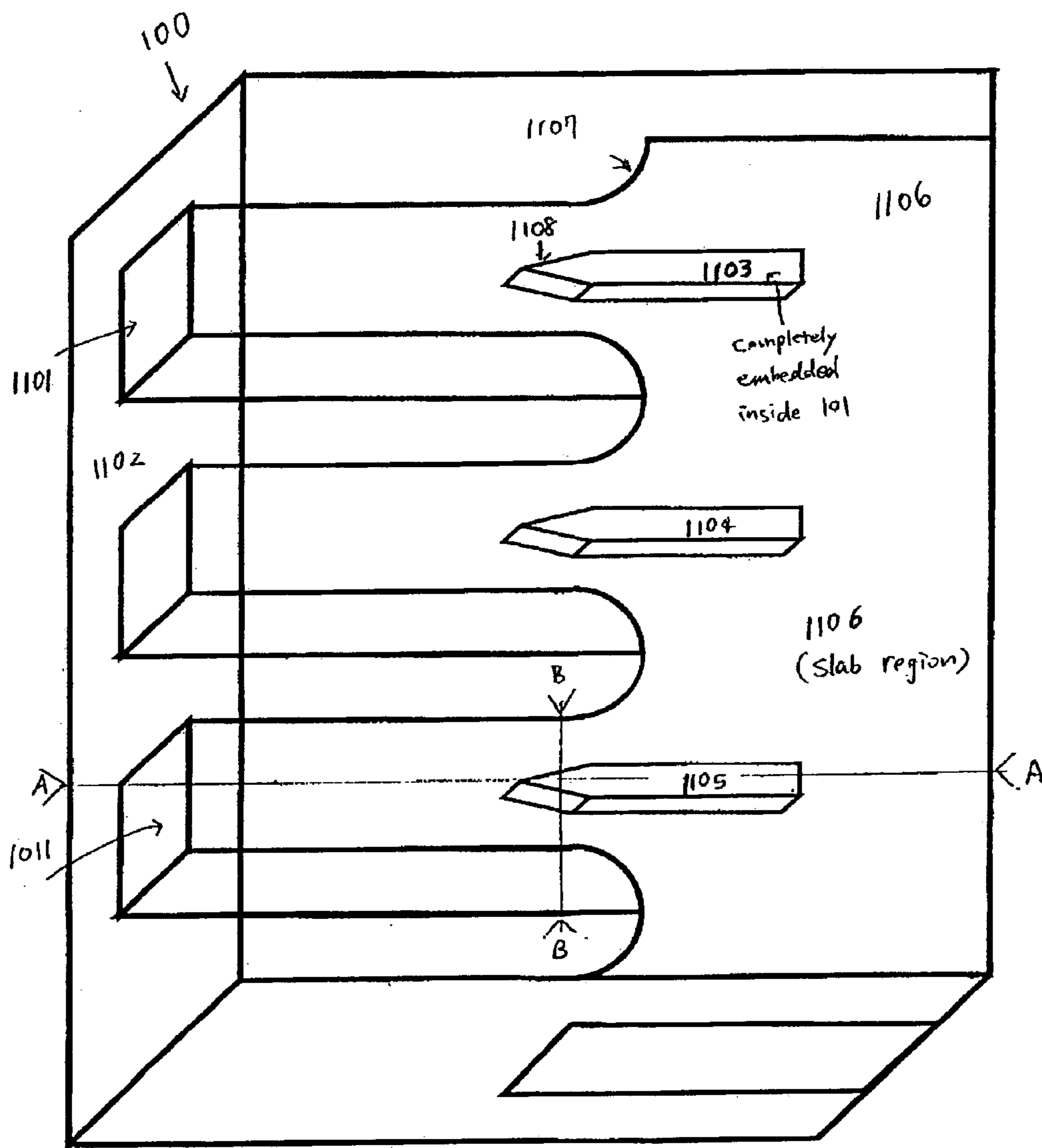


Figure 21

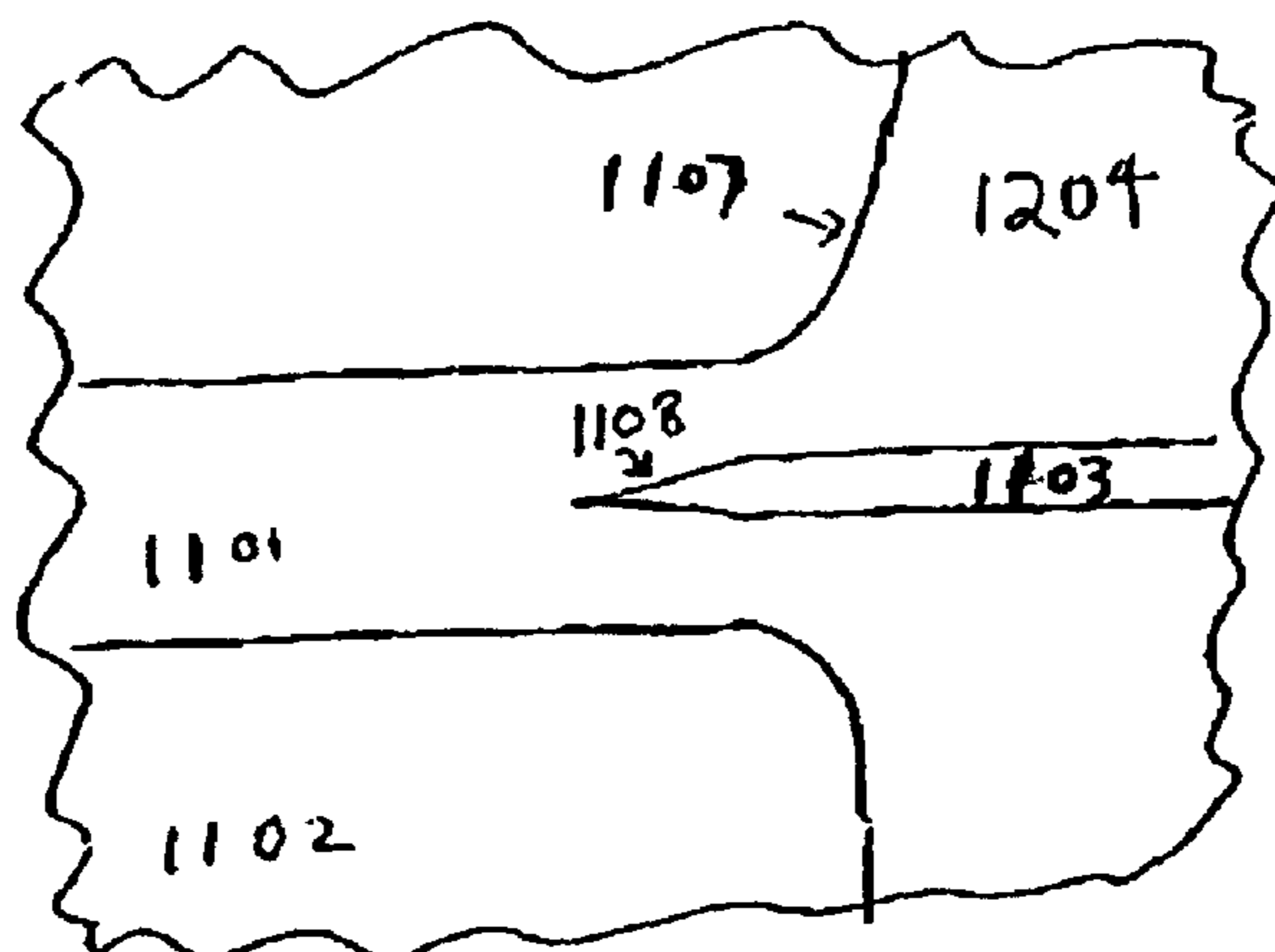


Figure 22

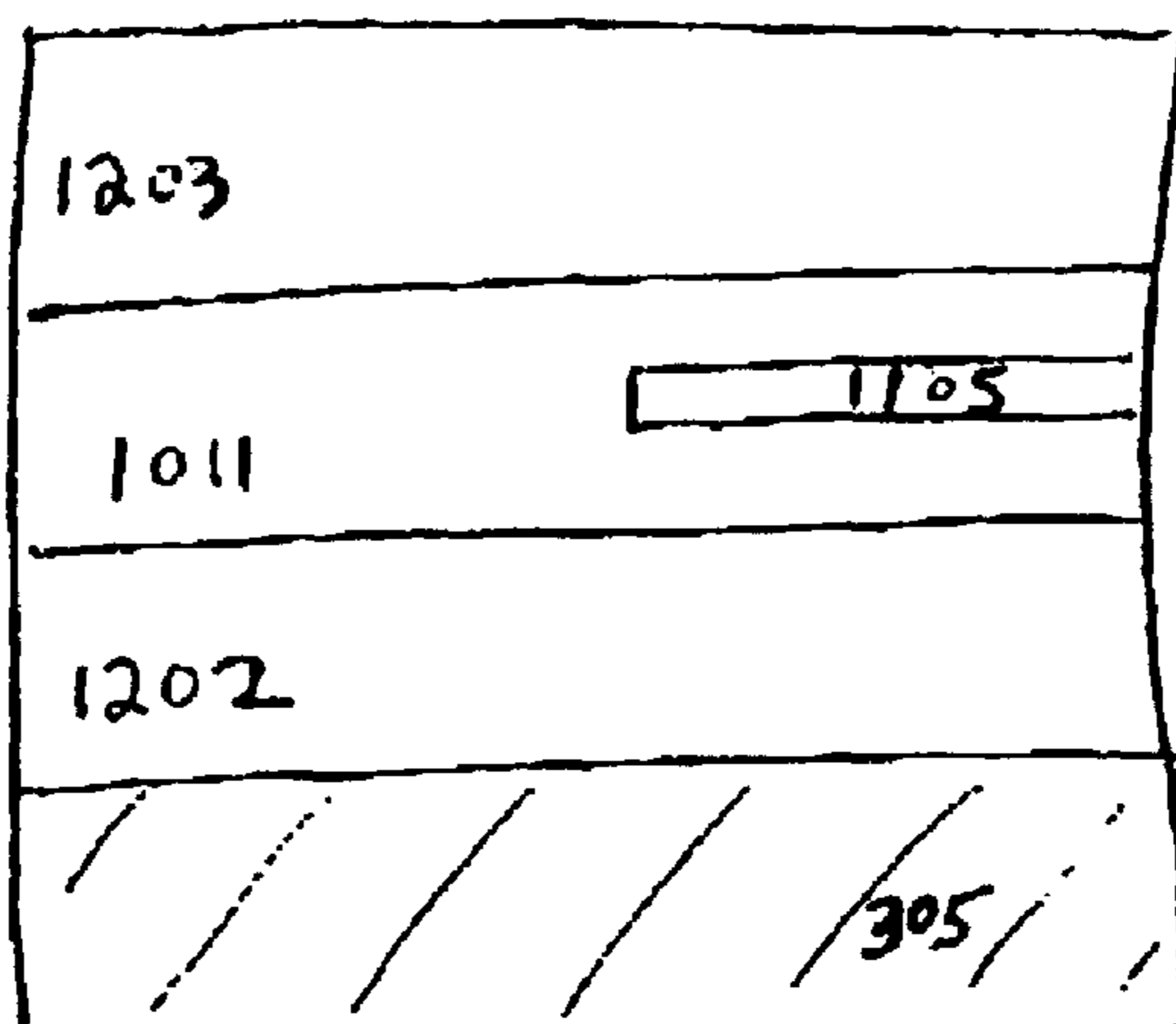


Figure 23

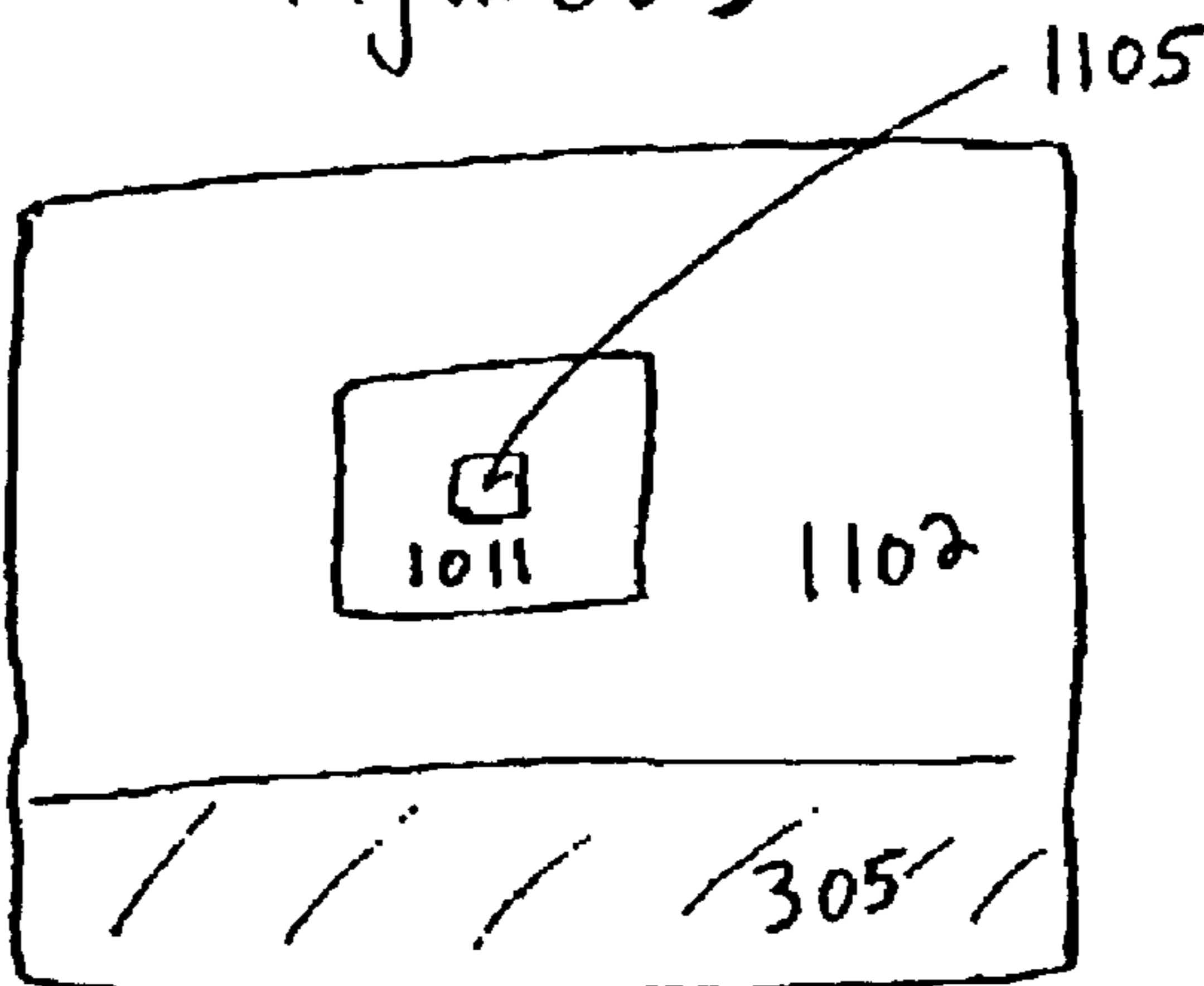


Figure 24

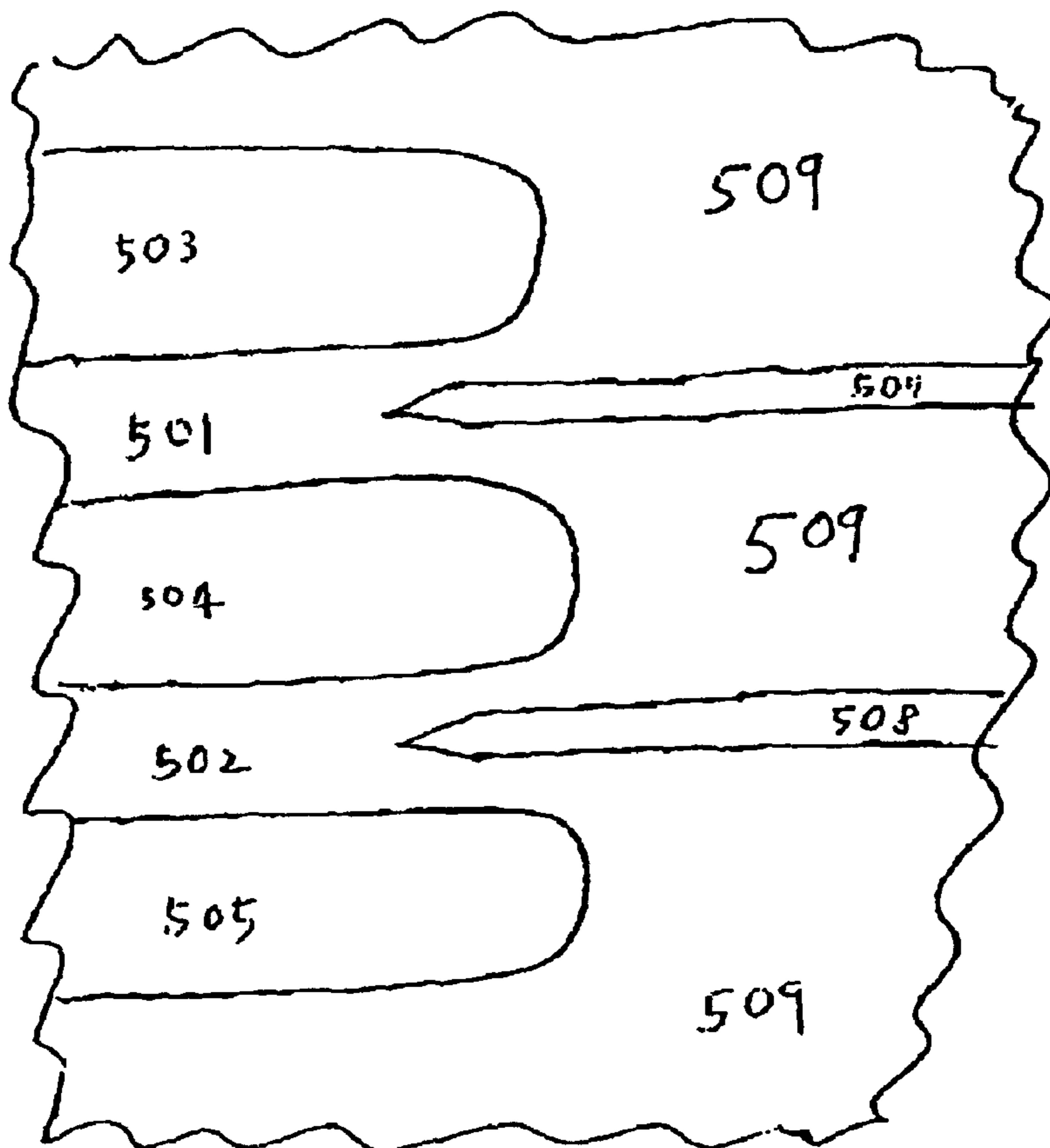


Figure 25

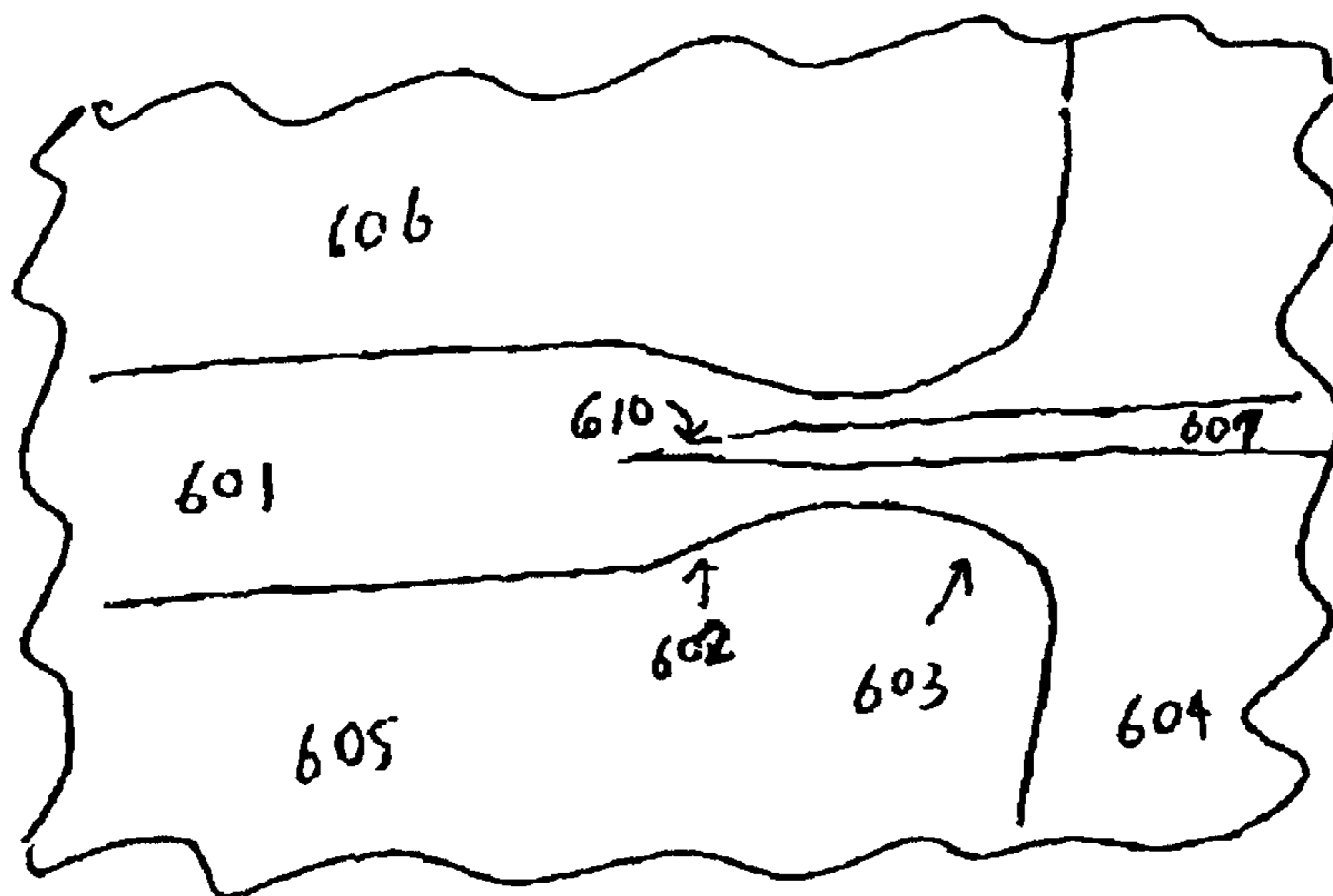
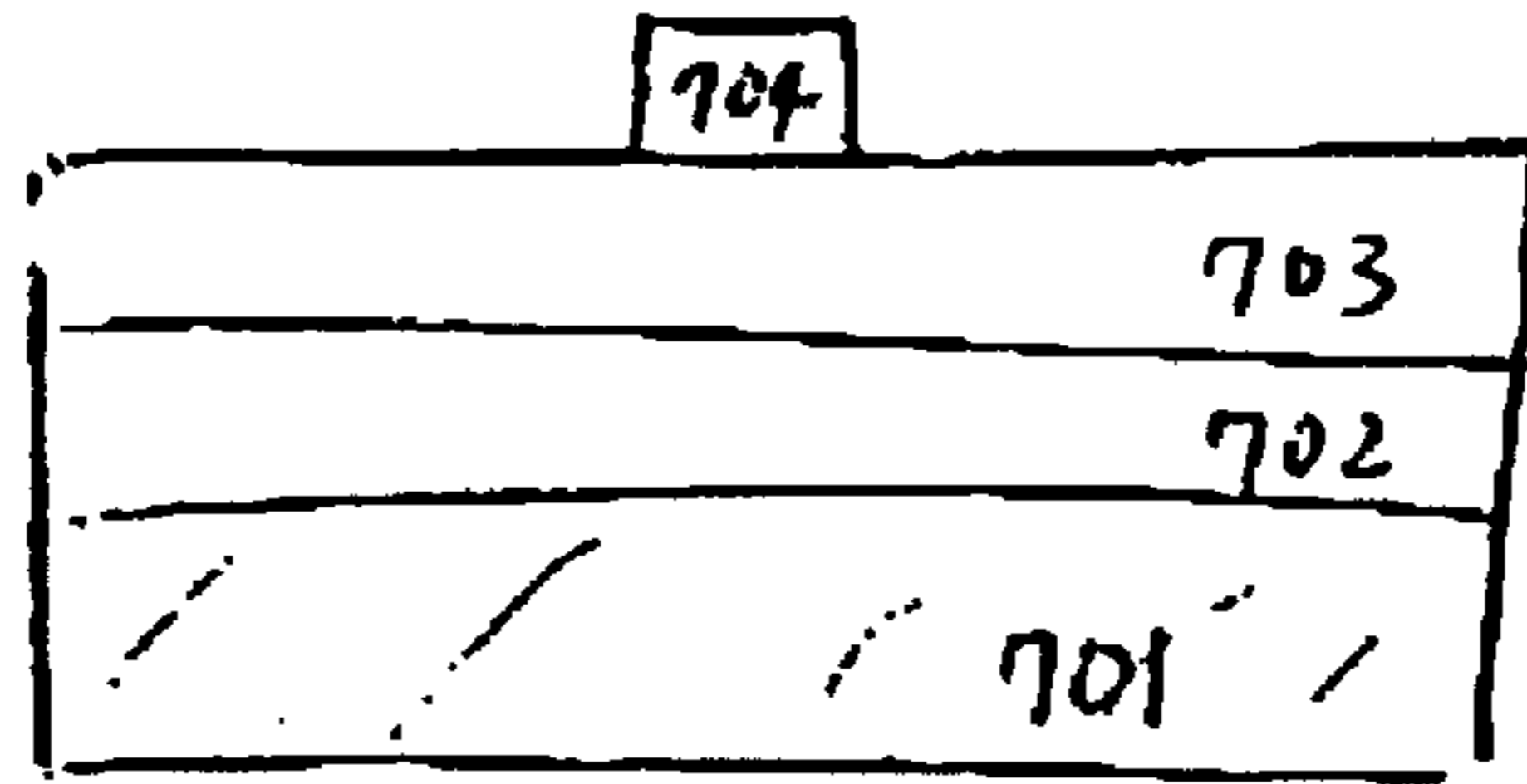
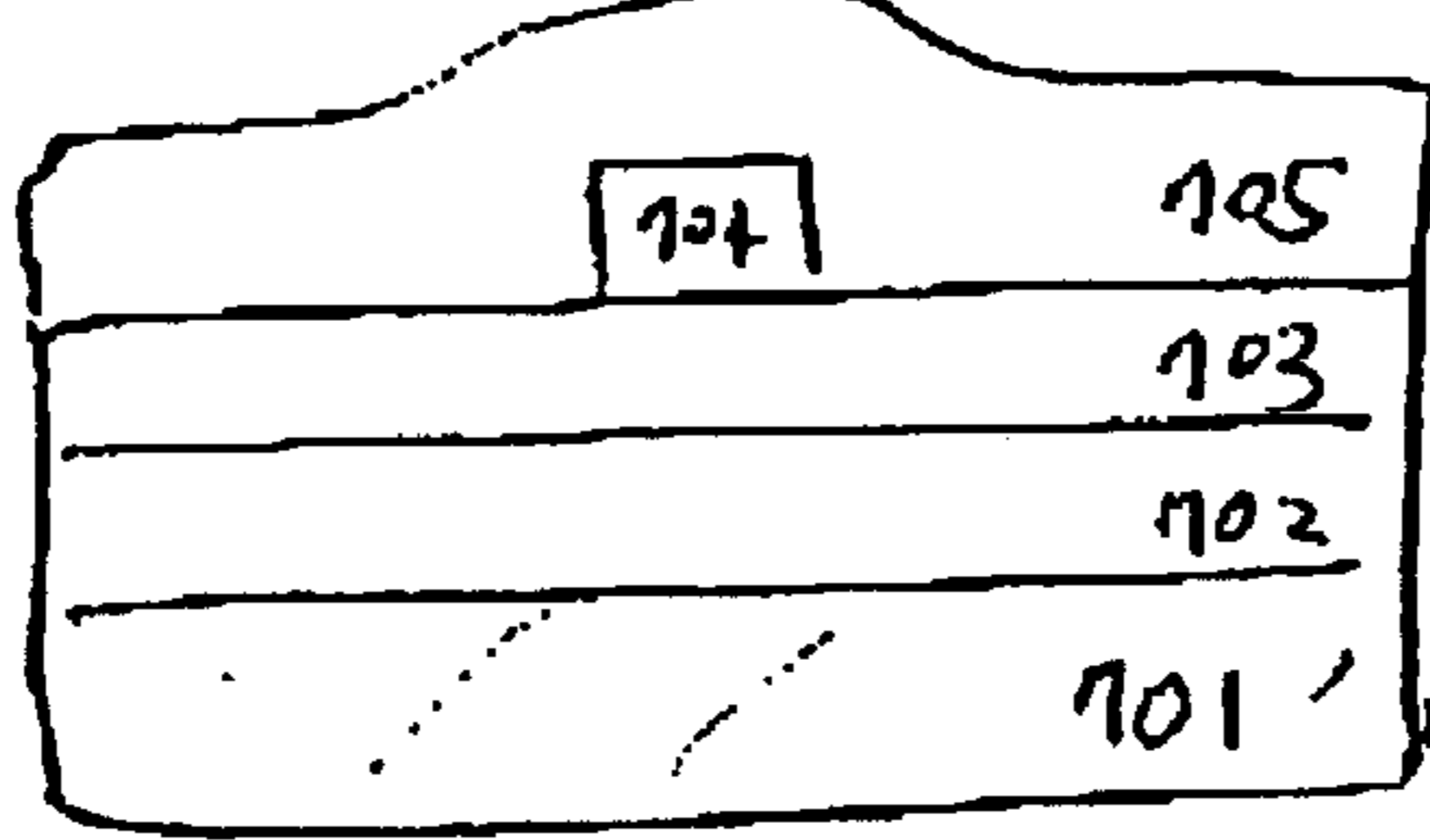


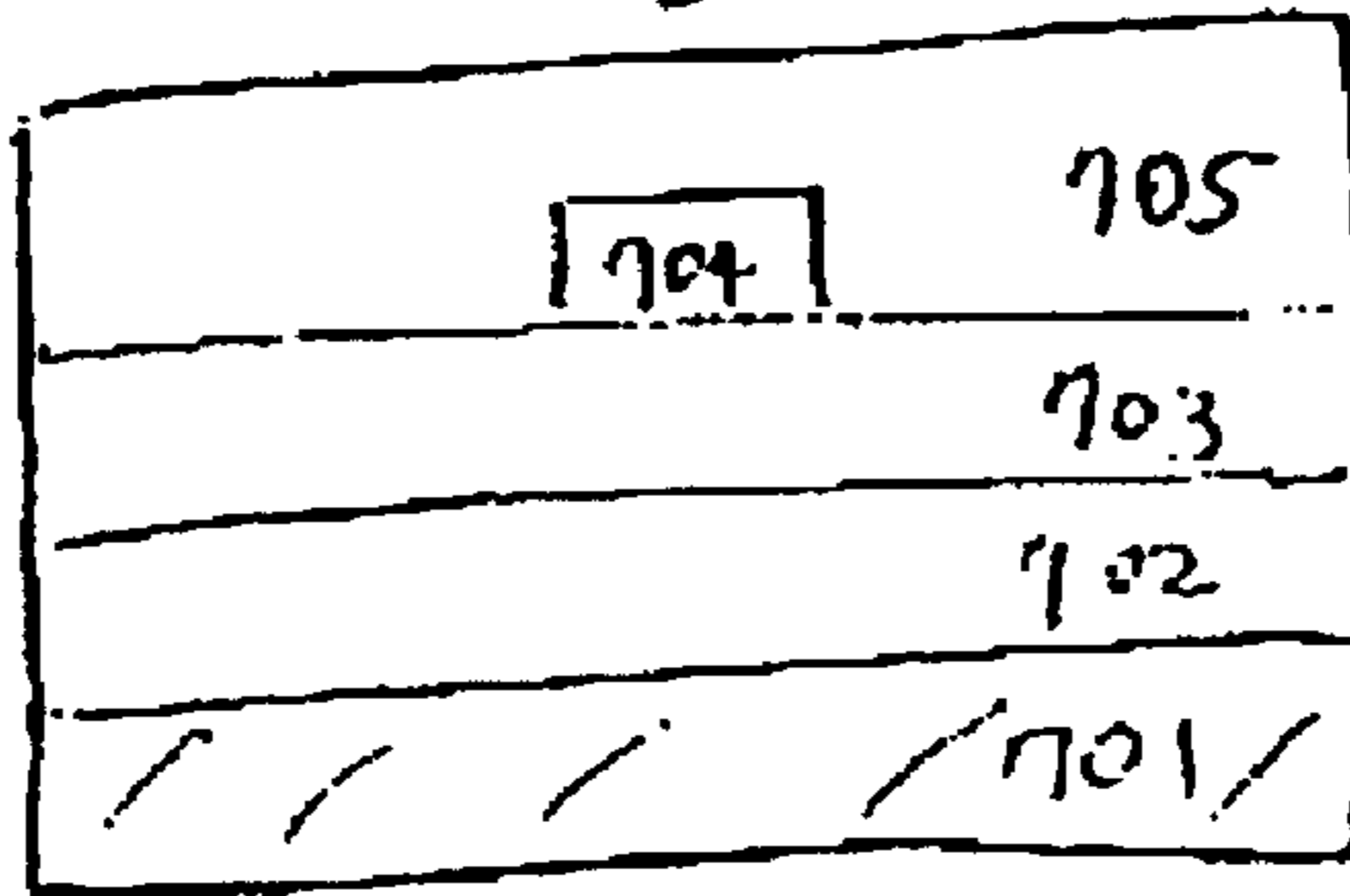
Figure 26



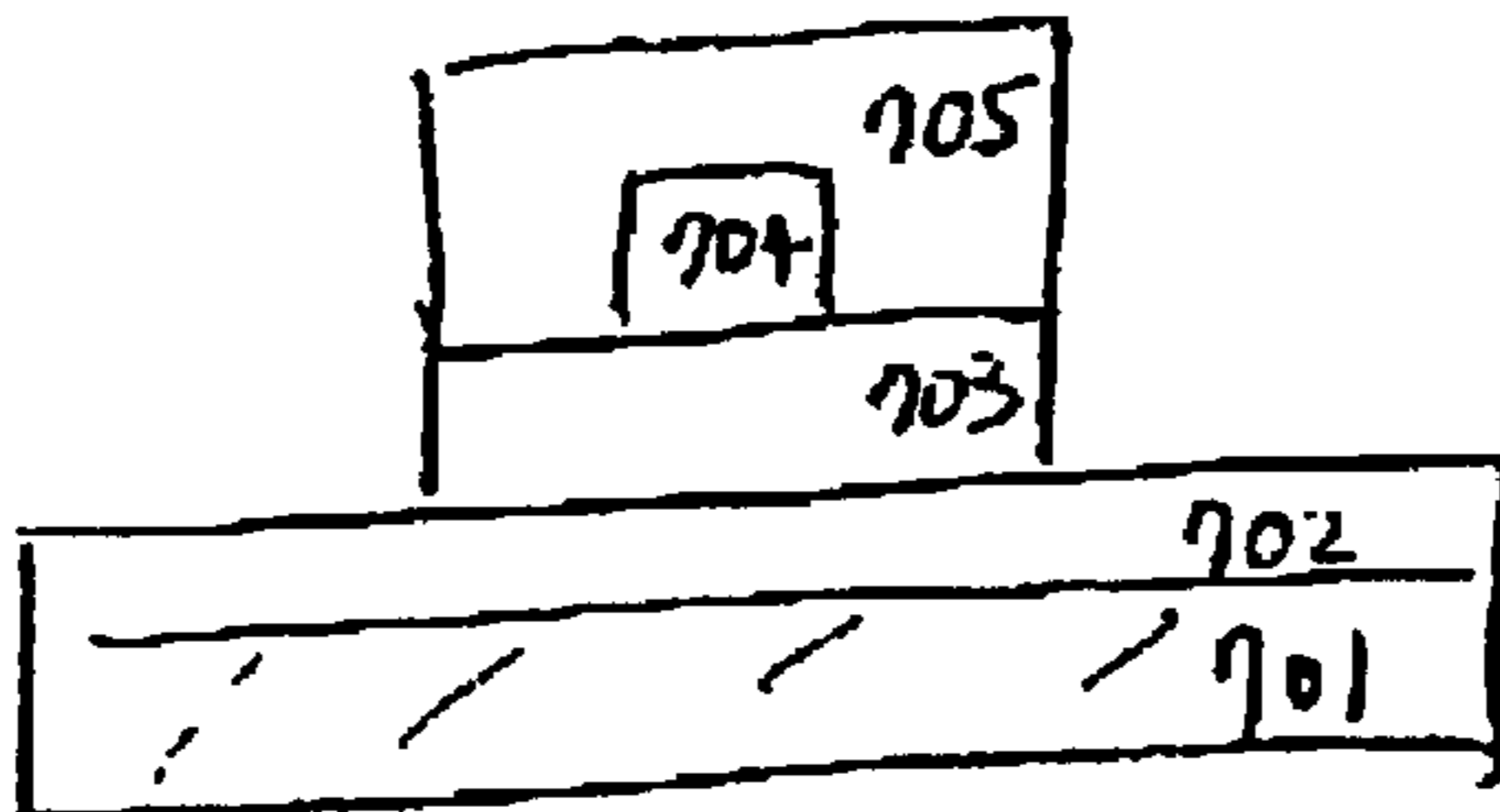
27A



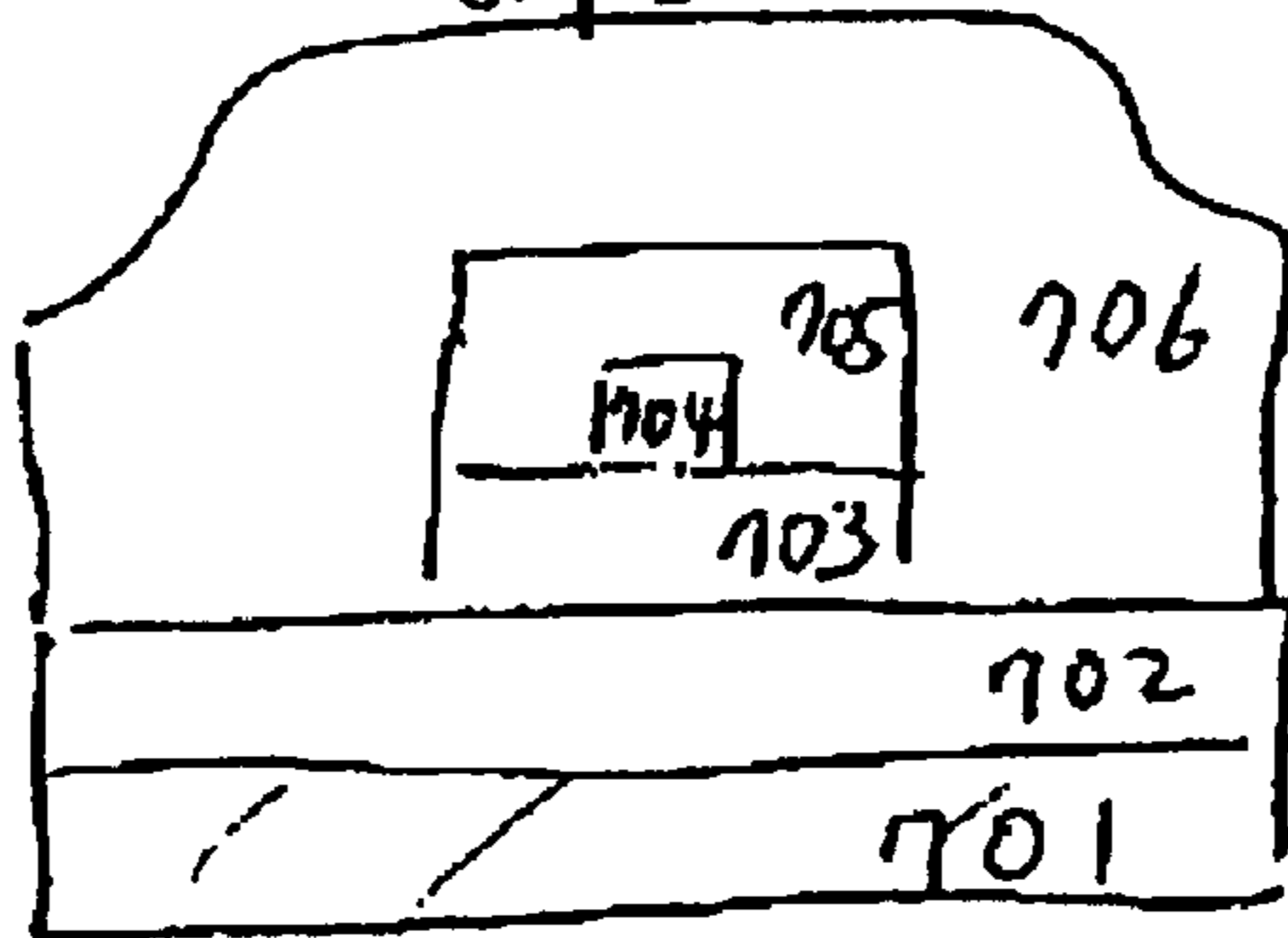
27B



27C



27D



27E

Figure 21

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EMBEDDED MODE CONVERTER

FIELD

The present invention relates generally to an optical converter and, more generally, to an optical converter for bi-directionally converting the optical mode between two waveguides.

BACKGROUND OF THE INVENTION

Integrated optical chips with optical functions typically use low index difference waveguides, and these optical chips generally contain up to only two or three optical functions. FIG. 1 shows a typical planar dielectric waveguide, which is an example of a two-dimensional waveguide. Low index difference waveguides, such as those used in optical chips and for the optical fiber waveguides for input to and output from optical chips, are three-dimensional versions of such planar dielectric waveguides. These low index difference waveguides **10** include a core material **12** surrounded by a cladding material **14**. The core material **12** can have an arbitrary cross-section, including a circular, elliptical, square, or rectangular cross-section embedded in the cladding material **14**. The index of refraction n_1 of the core material **12** is slightly larger than the index of refraction n_2 of the cladding material **14**. The index difference Δn for the index of refraction n_1 of the core material **12** and the index of refraction n_2 of the cladding material **14** ($\Delta n = n_1 - n_2$) is therefore generally very small. A useful metric is delta (Δ), which is defined as $\Delta n / n_{cladding}$ for this type of waveguide, and is generally around 0.01 (1 percent) to 0.04 (4 percent), and certainly less than 0.1 (10 percent). In other words:

$$\Delta = \frac{n_1 - n_2}{n_2} \ll 1.$$

A ray of light moving in the z direction in FIG. 1 (from left to right) is guided by total internal reflection within the core material **12** if the angle of incidence θ of the ray with respect to the interface between the core material **12** and the cladding material **14** is larger than a critical angle θ_c . This critical angle θ_c equals $\sin^{-1}(n_2/n_1)$. For low index difference waveguides, due to the indices of refraction n_1 , n_2 , the angle of incidence θ must be large in order for total internal reflection to guide the light ray through the waveguide.

The typical optical chips having low index difference waveguides are generally large, wafer-sized chips. This large size results because the low index difference waveguides can adequately guide light only if bends in the waveguides have large radii. If small bending radii are used with these low index difference waveguides, large losses result because light is loosely confined within the core material **12**. Low index difference waveguides therefore function adequately without large losses only with relatively high bending radii, and it is therefore difficult to perform optical functions in small areas using these low index difference waveguides.

The use of higher index difference waveguides reduces the minimum bending radii while maintaining adequate performance (that is, low loss), and therefore reduces the area required to perform the optical functions. The index of refraction n_1 of the core material **12** is significantly larger than the index of refraction n_2 of the cladding material **14** for such a higher index difference waveguide. Delta (Δ) for a

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high index difference waveguide is typically at least as large as 0.1, 0.2, or 0.3. In other words:

$$\Delta = \frac{n_1 - n_2}{n_2} \geq 0.1.$$

In such a high index difference waveguide, total internal reflection of light propagating through the waveguide is achieved for smaller angles of incidence θ for a ray of light, and the minimum bending radii for which performance is adequate is reduced.

The use of high index difference waveguides does have drawbacks. Because the fiber optic waveguides used for input to and output from optical chips are typically low index difference waveguides, a higher loss results in the coupling between the low index difference optical fiber waveguides and the high index difference waveguides on the optical chip. In addition, scattering loss increases for higher index difference waveguides, and therefore a larger loss in optical signals can result over a shorter length than for typical low index difference waveguides.

The mode converter between two different waveguides is an important part of an optical system where the lightwave (mode) from one optical component is to be transformed into the mode of another component. In optical communication, the mode converter between an optical fiber waveguide, which is typically a low index difference waveguide, and a high index difference planar waveguide can be important for the successful implementation of highly integrated optical circuits.

When converting the modes between two waveguides with different index differences and/or core indices, a coupling loss arises due to the differences in the mode size, shape, and mode velocity between the two waveguides. For example, the index difference and the mode of a fiber optic waveguide are different from those of a high index difference planar waveguide, resulting in a high coupling loss when the fiber optic waveguide and the high index difference planar waveguide are coupled directly. The index difference of a fiber optic waveguide is smaller than that of a high index difference waveguide, making the mode of the fiber optic waveguide larger than the mode of the high index difference waveguide. In addition, the core index of the fiber optic waveguide is lower than that of the high index difference planar waveguide, which causes a mode velocity difference between the two waveguides. When such changes in mode properties take place too quickly, a high power loss can arise.

SUMMARY OF THE INVENTION

One embodiment of the invention features a high density integrated optical chip. Under one aspect of the invention, the optical chip features a low minimum bending radius dielectric waveguide, a large mode field size dielectric waveguide, and an optical function. The optical function is connected to the low minimum bending radius dielectric waveguide, and the large mode field size dielectric waveguide interfaces with an external optical device, such as an optical fiber. The large mode field size dielectric waveguide is optically connected to the low minimum bending radius dielectric waveguide on the optical chip. The optical function can be any structure or device that is used to generate, modify, and/or measure the amplitude, frequency, wavelength, dispersion, timing, propagation direction, and/or polarization properties of one or more light pulses. In other embodiments, a plurality of low minimum bending radius dielectric waveguides and optical functions

can exist on the optical chip, and the low minimum bending radius dielectric waveguides can connect the optical functions. Such an embodiment can include a plurality of large mode field size dielectric waveguides used for input/output for the optical chip. These embodiments allow large numbers of optical functions to be integrated on a single optical chip having a small footprint.

According to another aspect of the invention, the optical chip described above can feature a low minimum bending radius dielectric waveguide including a high index core material, a cladding region generally surrounding the high index core material, and a graded index region applied between at least one side of the high index core material and the cladding region. This graded index region reduces scattering loss at the interface between the high index core material and the cladding region.

According to another aspect of the invention, a coupler can be used to couple a low index difference waveguide to a high index difference waveguide. Such a coupler, in one embodiment, can feature a high index difference waveguide embedded inside a low index difference waveguide. The high index difference waveguide tapers down toward the low index difference waveguide for low-loss mode conversion. The low index difference waveguide, in which the high index difference waveguide is embedded, tapers out toward the high index difference waveguide to terminate into a large slab region. Thus, the core of the low index difference waveguide becomes the cladding of the high index difference waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a prior art planar dielectric waveguide.

FIG. 2 is a block diagram of an optical chip according to one embodiment of the invention.

FIG. 3 is an enlarged cross-sectional view of a portion of the optical chip of FIG. 2.

FIG. 4 is a block diagram of two optical chips according to a second embodiment of the invention.

FIG. 5 is an enlarged cross-sectional view of a portion of the optical chip of FIG. 4 according to an embodiment of the invention.

FIG. 6 is top view of a schematic diagram of an exemplary embodiment of a mode transformer according to one aspect of the invention.

FIG. 7 is a side view of the mode transformer of FIG. 6.

FIG. 8 is a cross-sectional view of the mode transformer of FIGS. 6 and 7 in the embedded portion 112.

FIG. 9 is a cross-sectional view of the mode transformer in the low index core on the left side of FIGS. 6 and 7.

FIG. 10 is a cross-sectional view of the mode transformer in the high index core on the right side of FIGS. 6 and 7.

FIG. 11A is a cross-sectional view of the mode transformer of FIGS. 6 and 7.

FIGS. 11B–11I are graphs of exemplary refractive index profiles along line 5–5 of FIG. 11A.

FIG. 12 is a top view of a schematic diagram of an exemplary mode transformer in which the taper tips are optically in contact, but are not in physical contact.

FIG. 13 is a cross-sectional view of an exemplary embodiment of a graded index planar waveguide in accordance with an aspect of the invention.

FIG. 14 is a graph of an exemplary refractive index profile along a cross-section of FIG. 13.

FIG. 15 is a diagram of the fabrication steps for the graded index waveguide of FIG. 13 using a thin film deposition technique.

FIG. 16 is a perspective block diagram of an initial SOI platform 100 on which a waveguide is formed;

FIG. 17 is a perspective block diagram of the platform of FIG. 16 including a waveguide core after a typical patterning process;

FIG. 18 is a perspective block diagram of the platform of FIG. 17 after the surfaces of the core have reacted with the oxidizing agents and form a coating layer of SiO₂; and

FIG. 19 is a perspective block diagram of the platform of FIG. 18 following the removal of the SiO₂ layer to show the silicon core surface after smoothing.

FIG. 20 is a perspective block diagram showing the fabrication steps of an anisotropic etching waveguide, for which the substrate is (100) Si and the SiO₂ mask is aligned in the <110> direction so that the resulting Si core reveals {111}-type surfaces on the sidewalls.

FIG. 21 is a perspective view of a schematic diagram of an exemplary embodiment of a second mode transformer, with three mode couplers, according to one aspect of the invention.

FIG. 22 is a top view of one of the mode couplers of FIG. 21.

FIG. 23 is a side cross-sectional view of one of the mode couplers of FIG. 21 along line A—A.

FIG. 24 is a front cross-sectional view of one of the mode couplers of FIG. 21 along line B—B.

FIG. 25 is a top view of the mode transformer of FIG. 21.

FIG. 26 is a top view of a variation of one of the mode couplers of FIG. 21.

FIGS. 27A–27E are diagrams that show one method of fabrication of the mode transformer of FIG. 21.

DETAILED DESCRIPTION OF THE EMBODIMENTS OF THE INVENTION

The embodiments of the invention provide optical chips with low minimum bending radius waveguides. Very briefly, the optical chip includes one or more low minimum bending radius waveguides and optical functions integrated with one or more large mode size waveguides. The large mode size waveguide is used to communicate with optical devices that are external to the optical chip. These external optical devices can include optical fibers or other optical chips.

FIG. 2 is a top view of an optical chip according to a first embodiment of the invention. The optical chip of FIG. 2 includes at least one large mode size waveguide 22, at least one low minimum bending radius waveguide 24, and at least one optical or electro-optical function 26 fabricated on a substrate 20. The embodiment of the optical chip of FIG. 2 depicts two low minimum bending radius waveguides 24, with each low minimum bending radius waveguide 24 being optically connected to a different large mode size waveguide 22 and optical function 26. In other embodiments, a single large mode size waveguide 22, a single low minimum bending radius waveguide 24, and a single optical function 26 can be disposed on the substrate 20, and in still other embodiments more than two of each of these components can be disposed on the substrate 20.

The large mode field size waveguide 22, low minimum bending radius waveguide 24, and optical function 26 are fabricated monolithically on a single substrate 20. A number of other components can also be bonded in any manner on

the substrate **20**, including separate optical functions or waveguides. The substrate **20** can be made from any material, including silicon, indium phosphide, ceramic, or quartz. The substrate **20** can also be shaped in a variety of forms, including a rectangular, square, elliptical, or circular shape with a thin side profile. Generally, an optical chip includes a planar substrate **20** and patterned core materials and cladding layers that define a planar lightwave circuit (PLC) or optical circuit. At least one large mode field size waveguide **22** on the substrate **20** has a first end **30** that terminates on a side, edge, or accessible portion of the substrate **20** so that it can be connected to an external optical device, such as the optical fiber **28** shown in FIG. **2**. A second end **32** of the large mode field size waveguide **22** can be optically coupled to one of the low minimum bending radius waveguides **24** on the substrate **20**. The large mode field size waveguide **22** on substrate **20**, therefore, can serve as an input/output port for the optical chip. Further, the optical chip can contain functions that change the information carrier signal from an optical signal to a difference form of energy, or vice versa. Examples of alternate forms of energy that carry information include acoustic (sound/audio), radio frequency, infrared, and microwave, as well as other bands of the electromagnetic spectrum.

At least one optical function **26** is connected to one of the low minimum bending radius waveguides **24** on the substrate **20**. An optical function **26** is generally any structure or device that is used to generate, modify, and/or measure the amplitude, frequency, wavelength, dispersion, timing, propagation direction, and/or polarization properties of one or more light pulses. Optical functions **26** can include splitters, couplers, modulators, switches, filters, isolators, detectors, and amplifiers. A single optical function **26**, therefore, is a structure that performs at least one function, such as those listed above. The optical function or functions **26** can be chosen for a wide variety of applications. In addition, the optical functions **26** can be integrated with electrical functions and electro-optical functions on a single substrate **20**. If a single optical chip contains multiple optical or electro-optical functions **26**, low minimum bending radius waveguides **24** can be used to interconnect these optical or electro-optical functions **26**.

FIG. **3** is a cross-sectional view of the optical chip of FIG. **2** that shows a single large mode field size waveguide **22** and a single low minimum bending radius waveguide **24** coupled on the substrate **20**. A coupler or transformer **100** is used to couple the large mode field size waveguide **22** to the low minimum bending radius waveguide **24** on the substrate **20**. A variety of couplers or transformers **100** can be used within the scope of the invention to provide this coupling function. One suitable coupler **100** is described in detail below.

The large mode field size waveguide **22** can, in one embodiment, be a low index difference waveguide that is a channel waveguide, although in other embodiments other types of waveguides can be used as the large mode field size waveguide **22**. Generally, the large mode field size waveguide has a mode field size similar to that of external optical fiber, which is a low index difference waveguide. The low index difference waveguide **22** of FIG. **3** includes a core material **42** having an index of refraction n_1 and a cladding material **46** having an index of refraction n_3 . Similarly, the high index difference waveguide **24** includes a core material **44** having an index of refraction n_2 and a cladding material **46** having an index of refraction n_3 . The index of refraction n_3 of the cladding material **46** is less than the index of refraction n_1 of the low index core material **42**, which is less than the index of refraction n_2 of the high index core

material **44**. In the embodiment of FIG. **3**, the low index difference waveguides **22** and the low minimum bending radius waveguide **24** both have the same cladding material **46** surrounding their cores **42**, **44**, although in other embodiments different cladding materials can be used. As used throughout this specification, a low index difference waveguide is a waveguide where delta (Δ) for the index of refraction n_1 of the core material **42** and the index of refraction n_3 of the cladding material **46** is generally very small, such as less than 0.1 (10 percent). In other words:

$$\Delta = \frac{n_1 - n_3}{n_3} < 0.1.$$

In some embodiments, this index difference Δn is such that Δ is less than 0.01 (1 percent) or less than 0.04 (4 percent). A high index difference waveguide, on the other hand, is a waveguide where delta (Δ) for the index of refraction n_2 of the core material **44** and the index of refraction n_3 of the cladding material **46** is at least 0.1. In other words:

$$\Delta = \frac{n_2 - n_3}{n_3} \geq 0.1.$$

In other embodiments, the index difference Δn is such that Δ for a high index difference waveguide is at least 0.2, and for still other embodiments, Δ is at least 0.3. In some embodiments of the invention, the low minimum bending radius waveguides **24** can be high index difference waveguides.

For the low index difference waveguide **22**, the index of refraction n_1 of the core material **42** and the index of refraction n_3 of the cladding material **46** are chosen so that the low index difference waveguide **22** has an effective index of refraction and mode size close to that of the external optical fiber **28**. The external optical fiber **28** includes a core material **48** surrounded by a cladding material **49**. The core material **48** of the optical fiber **28** can have a square, rectangular, elliptical, or circular cross-section or, in other embodiments, an arbitrary cross-section can be used. In one embodiment, the same geometry and indices of refraction can be chosen for the low index difference waveguide **22** on the substrate **20** as are used for the external optical fiber **28**. The coupling loss between the external optical fiber **28** and the low index difference waveguide **22** is minimized by matching the mode size of the low index difference waveguide **22** to that of the external optical fiber **28**. In addition, reflection is minimized by matching the effective index of refraction of the low index difference waveguide **22** to that of the external optical fiber **28**.

The indices of refraction n_1 , n_3 of the low index core **42** and the cladding material **46** are, in one embodiment, chosen so that the low index difference waveguide **22** has a mode field $1/e$ diameter size of at least 2 microns. The mode field $1/e$ diameter (the mode size) is the diameter of the mode where the optical field amplitude is $1/e$ of the peak optical field amplitude. In this embodiment, the core material **42** and the cladding material **46** are chosen to make the mode field $1/e$ diameter size large enough to maximize the coupling throughput and error tolerance with the external optical fiber **28**.

To design a waveguide by mode size, the following procedure can be used. For a particular selection of refractive indices n_1 , n_3 and for a certain wavelength of light that will propagate through the waveguide, the dimensions of the waveguide can be selected to be less than or equal to the single mode cut-off dimension, and this dimension deter-

mines the mode size. The lower limit of the mode field 1/e diameter size of about 2 microns, therefore, ensures that the mode field 1/e diameter size of the low index difference waveguide **22** will remain large enough to effectively couple to external optical fibers **28**. In other embodiments, this lower limit of the mode field 1/e diameter can be about 3 microns or, in still other embodiments, 5 microns. Typical optical fiber waveguides have mode field 1/e diameter sizes of about 8–10 microns. In one embodiment, therefore, the low index difference waveguide **22** can have a mode field 1/e diameter size of about 8–10 microns. An upper range of the mode field 1/e diameter size of the low index difference waveguide **22** can be the largest mode field 1/e diameter size typically used for external optical fibers **28**. In one embodiment, such an upper range for the mode field 1/e diameter size can be about 15–20 microns, although this upper mode field 1/e diameter size can vary widely.

Throughout this specification, a large mode field size waveguide (or large mode size waveguide) is a waveguide that has a mode field 1/e area similar to that of a waveguide having a mode field 1/e diameter of at least 2 microns. In such an embodiment, for instance, the mode field 1/e area would be π square microns. Similarly, in an embodiment where the mode field 1/e diameter is 3 microns, the mode field 1/e area would be about 2.25π square microns. More particularly, a large mode field size waveguide could have a mode field 1/e area of about 16π square microns (for an 8 micron mode field 1/e diameter) or 25π square microns (for a 10 micron mode field 1/e diameter). Such a large mode field size waveguide having an 8–10 micron diameter can include optical fiber. A large mode field size waveguide can be a waveguide of any configuration, including but not limited to a channel waveguide.

In one embodiment, as mentioned above, the large mode field size waveguide **22** on the substrate **20** can be a low index difference waveguide **22**. The low index difference waveguide **22** can have a core material **42** made from silica and a cladding material **46** made from doped silica. A blunt connection or coupler of any variety can be used to connect the external optical fiber **28** to the low index difference waveguide **22** on the substrate **20**. For instance, an end of the optical fiber **28** can be abutted to an end of the low index difference waveguide **22**, and these two ends can be adhered together. Because the material and design of the low index difference waveguide **22** can be chosen to match the external optical fiber **28**, a low coupling loss, such as about 1 decibel (dB) or less, can result between the external optical fiber **28** and the low index difference waveguide **22**. The external optical fiber **28** shown in FIGS. **2** and **3** can be replaced by any low index difference waveguide, and not only the optical fiber **28** shown in the Figures. The external optical fiber **28** could therefore represent an input or output from another optical chip on a substrate or could be any other optical device.

The low minimum bending radius waveguide **24** allows for the miniaturization of optical functions **26** on the substrate **20**. A small optical chip with a large number of optical functions **26** can therefore result. Because low minimum bending radius waveguides have smaller bending radii than large mode size waveguides and low index difference waveguides, optical functions **26** and bending and splitting of propagating light can be implemented in smaller areas using these low minimum bending radius waveguides. A “minimum bending radius” can be defined as the radius for a 90 degree bend in which the loss during the bend is less than or equal to a certain amount, such as 0.5 dB in one embodiment. In other embodiments, a minimum bending

radius can be for a loss of less than or equal to 0.1 dB in a 90 degree turn or, in still other embodiments, a loss of less than or equal to 0.01 dB in a 90 degree turn. Throughout this specification, the term “low minimum bending radius” will be used to refer to a radius of less than or equal to 50 microns for a 90 degree bend in which the loss during the bend is less than or equal to 0.5 dB. As an example, the minimum bending radius for a high index difference waveguide having a delta (Δ) of 0.3, $n_{cladding}$ of 1.5, and having a 1 micron by 1 micron core dimension can be less than or equal to 50 microns and, in other embodiments, less than or equal to 20 microns, and in still other embodiments, less than or equal to 10 microns. Such a waveguide is a low minimum bending radius waveguide. As another example, the minimum bending radius for a low index difference waveguide where Δ is 0.01, $n_{cladding}$ is 1.5, and having a 10 micron by 10 micron core dimension is on the order of 1 cm. Such a waveguide is not a low minimum bending radius waveguide.

The use of low minimum bending radius waveguides on the optical chip allows for the integration of a large number of optical functions **26** on a single substrate **20**. The optical functions **26** and low minimum bending radius waveguides **24** on the substrate **20** communicate with external optical fibers **28**, chips, or optical devices through the large mode field size waveguides **22** on the substrate **20**. Whereas typical wafer-sized chips with low index difference waveguides can be approximately 10 centimeters by 10 centimeters in dimension with about 1 to 3 or 4 optical functions, an optical chip on substrate **20** using low minimum bending radius waveguides **24** can be about 1 centimeter by 1 centimeter in dimension with 1 to 10,000 or more optical functions. In any event, more than 5 or more than 10 optical functions can be performed on substrate **20** using low minimum bending radius waveguides in a smaller area than is used for wafer-sized chips using low index difference waveguides.

As mentioned above, the large mode size waveguides can be low index difference waveguides and the low minimum bending radius waveguides can be high index difference waveguides in one embodiment of the invention. The following discussion is for such an embodiment, although other large mode size waveguides and low minimum bending radius waveguides can be used in other variations of the embodiments disclosed below.

Referring again to FIG. **2**, the optical chip can contain more than one input or output low index difference waveguides **22**. In FIG. **2**, for instance, a first low index difference waveguide **22** provides for a first input/output port from the optical chip, and a second low index difference waveguide **22** provides for a second input/output port from the optical chip. In addition, each of the optical functions **26** depicted in FIG. **2** could be coupled to more than one high index difference waveguide **24**. The particular design of the optical chip depends on the application for which the optical chip will be used.

FIG. **4** depicts a second embodiment of an optical chip in accordance with the invention. The embodiment of FIG. **4** is similar to that of FIG. **2**, except that an optical connection is made between one of the low index difference waveguides **22** on the substrate **20** and an external chip **60** (the left side of FIG. **4**) rather than an external optical fiber. FIG. **4** does, however, show a second optical connection made between a low index difference waveguide **22** on the substrate **20** and an external optical fiber **28** (the right side of FIG. **4**). In FIG. **2**, both low index difference waveguides **22** are connected to external optical fibers **28**. Thus, FIG. **4** illustrates the possibility that optical signals can be transferred directly

between low index difference waveguides on separate optical chips. The low index difference waveguide 22 on substrate 20 can therefore directly connect to external chips 60 as well as to external optical fibers 28. In addition, as specifically shown in FIG. 4, a low index difference waveguide 62 on an external chip 60 can be used to couple with the low index difference waveguide 22 on the substrate 20.

FIG. 5 depicts an enlarged cross-sectional view of another embodiment in accordance with the invention. In the embodiment of FIG. 5, at least one emitting/receiving function 64 is fabricated on a second substrate 61 and is optically connected to the low index difference waveguide 22 on substrate 20. In this embodiment, the substrate 20 is similar to the embodiments described above. The substrate 20 therefore contains at least one low index difference waveguide 22 coupled to at least one high index difference waveguide 24, as well as an optical function (not shown in FIG. 5) optically connected to the high index difference waveguide 24. The emitting/receiving function 64 of FIG. 5 can be any of a variety of devices. For example, the emitting/receiving function 64 can be an edge emitting/receiving device or a vertically emitting/receiving device. Specific examples include surface-emitting LEDs, edge-emitting LEDs, and surface-emitting laser diodes. Surface-emitting/receiving optical functions are generally easier to fabricate than edge emitting/receiving functions, and some surface-emitting functions, such as surface-emitting LEDs, are more efficient than edge-emitting LEDs.

In the embodiment shown in FIG. 5, coupling between the low index difference waveguide 22 and the emitting/receiving function 64 is most efficient if the mode sizes of the waveguide 22 and the emitting/receiving function 64 are the same or are similar. The low index difference waveguide 22, therefore, can be designed to produce a mode size similar to that of the emitting/receiving function 64. It may, however, be difficult or impossible to effectively match the effective index of the emitting/receiving function 64 with that of the low index difference waveguide 22. For this reason, an anti-reflection coating 66 can be applied to an edge of the low index difference waveguide 22 on substrate 20 or on the emitting/receiving function 64 to suppress unwanted reflections and to aid in coupling efficiency. If, for example, the emitting/receiving function 64 on substrate 61 is a surface-emitting LED, an anti-reflection coating 66 can be applied to an edge of the low index difference waveguide 22 on substrate 20 or on the emitting/receiving function 64. Similarly, if the emitting/receiving function 64 on substrate 61 is a receiver, an anti-reflection coating 66 can be applied to this receiver or on the low index difference waveguide 22.

The embodiment of FIG. 5 shows that two or more optical chips can be optically connected through the use of the low index difference waveguide 22 on substrate 20. Substrate 20 contains high index difference waveguides 24 and optical functions 26, and yet external functions on separate optical chips with mode sizes similar to the low index difference waveguide 22 can be optically connected to the substrate 20 through low index difference waveguide 22. In still other embodiments, two or more optical chips, such as those shown in FIGS. 2-5, can be optically coupled. For instance, a first optical chip can contain a low index difference waveguide 22 coupled to a high index difference waveguide 24, which is in turn coupled to an optical function 26. A second optical chip can have a similar layout. These two optical chips can then be optically connected through the low index difference waveguides 22.

The optical chips described above can also be part of a larger subsystem. For instance, such a subsystem could

include one of the optical chips described above connected to an external large mode field size dielectric waveguide. The optical chip in such an embodiment could include a low minimum bending radius waveguide, an optical function connected to the low minimum bending radius waveguide, and a large mode field size waveguide coupled to the low minimum bending radius waveguide. The external large mode field size dielectric waveguide, in this embodiment, would be external to the optical chip and would be optically coupled to the large mode field size waveguide on the optical chip. Such a subsystem including an optical chip and an external large mode field size dielectric waveguide, one example of which can be a module, could be used in a number of applications, including those described below.

The optical chips described above can be used for a variety of applications, including passive or active applications. In one embodiment, the optical chips described above can be used for communications applications. As an example, a splitter can be fabricated to split a single optical signal into 8 or 16 or 32 signals in a small area. Typical splitters are made using series of 1-by-2 splitters to perform splitting functions. For example, fifteen 1-by-2 splitters would be needed to split a single signal into 16 signals. If low index difference waveguides are used, this splitting function would require a large footprint. An optical chip having high index difference waveguides, such as those described above, could perform this splitting function in a significantly smaller footprint.

Another communications application can be in multiplexing or demultiplexing. As an example, a wavelength division multiplexing (WDM) function can be implemented as an optical function 26 on substrate 20. Such a WDM function can include combining or filtering out different wavelengths of light, which represent different channels of information signals. An optical chip having low minimum bending radius or high index difference waveguides can perform such functions in a small footprint.

The optical chips can also be used in Ethernet applications to increase the speed and bandwidth of such systems through optical applications. The optical chips can, for instance, be used to perform optical functions to help make an Ethernet into an optical system with 10 gigabit per second performance. The optical chips can also enhance Ethernet applications by decreasing the space needed to perform optical functions.

The optical chips described above can also be used to enhance computing and microprocessing functions in optical or electro-optical circuits. These devices can include optical and electronic functions on a single chip, and can include digital or analog signal processing applications. As an example, an optical clock for synchronizing signals and modulating these signals can be fabricated on the optical chip.

Sensing applications can also be performed. As an example, an optical chip can be fabricated with high index difference waveguides, and changes in characteristics of the optical waveguide mode itself can be used to detect the presence of certain chemicals or changes in temperature. In short, the optical chips described above having low minimum bending radius or high index difference waveguides can be used in a variety of applications.

Further, the optical chip can contain functions that change the information carrier from an optical signal to a signal in an alternative form of energy, or vice versa. Examples of alternate forms of energy that carry information include acoustic (sound/audio), radio frequency, infrared, and microwave, as well as other bands of the electromagnetic

spectrum This function will allow the optical chip to interface fiber optic and generic light-wave communications methods with wireless communications with carrier frequencies ranging from kHz to tens of THz.

The optical chips can incorporate other popular current technology, such as MEMS, lasers, detectors, micro-resonators, interference devices, multi-mode interferometers, arrayed waveguide gratings, and Mach-Zehnder modulators as basic building blocks of functionality. Together with other devices, subsystems on a single optical chip, including both passive and active applications, can be implemented.

As described above, the substrate **20** contains at least one large mode size waveguide **22** coupled to at least one low minimum bending radius waveguide **24**. Two waveguides are “coupled” or “optically connected” if a change in one or more of the properties of an optical signal in one waveguide affects the properties of the optical signal in the second waveguide without an intermediate conversion to an electrical signal. Many optical couplers can be used in accordance with the invention. One such optical coupler is described in U.S. Pat. No. 6,253,015 to Ukrainczyk et al.

Generally, it can be desirable to have the lowest possible loss in optical signal in the coupler between a first waveguide and a second waveguide. This coupling loss, for instance, can be about 1 decibel or less for an efficient coupler. For coupling of waveguides having similar mode sizes and refractive indices, simple coupling methods, such as abutting an end of one waveguide to an end of the other waveguide, can be used. When the mode sizes of waveguides differ, however, more complex couplers can be used.

FIGS. 6–10 are simplified schematic diagrams of an exemplary embodiment of a first mode transformer or coupler **100** that can be used in accordance with the invention. Such a mode transformer or coupler **100** can be used as the coupler **100** on substrate **20** (FIGS. 2–5) to optically couple the large mode size waveguide **22** to the low minimum bending radius waveguide **24**, although such a coupler can be used for other coupling applications as well. In the embodiments of the coupler or mode transformer **100** described below, the large mode size waveguide **22** is a low index difference waveguide, and the low minimum bending radius waveguide **24** is a high index difference waveguide **24**, although, as mentioned above, other low minimum bending radius waveguides or large mode size waveguides can be used in other embodiments. FIG. 6 shows a top view of the mode transformer **100**, while FIG. 7 shows a side view of the same transformer **100**.

The mode transformer **100** includes a core material **102** of a low index difference waveguide (the left side of FIG. 6), a core material **104** of a high index difference waveguide (the right side of FIG. 6), and cladding material **106** surrounding both core materials **102**, **104**. The core material **104** and cladding material **106** on the left side define the low index difference waveguide, which forms a large mode, and the core material **102** and cladding material **106** on the right side define the high index difference waveguide, which forms a small mode. In one embodiment, both high and low index difference waveguides are channel waveguides. A channel waveguide is a waveguide having a core material surrounded on its sides by one or more cladding materials that have lower indices of refraction than that the core material. The cross-sectional shape of the core material in such a channel waveguide can be rectangular, square, elliptical, or circular. In other embodiments, the cross-sectional shape of the core material can be arbitrary. The

mode field distribution of light resides primarily within the core material of a channel waveguide. It is within this core material of a typical channel waveguide that the peak optical intensity of light typically resides. A channel-like mode is a mode that is defined by a core completely surrounded by a cladding, where the cladding is made of one or more materials with refractive indices lower than that of the core. Channel and strip waveguides are examples of waveguides with channel-like modes. The cross-sections of the mode transformer **100** shown in FIGS. 9 and 10 depict square core material shapes in the channel waveguides. FIG. 9 is a cross-sectional view of the left side of FIG. 6 in the low index core **102**, and FIG. 10 is a cross-sectional view of the right side of FIG. 6 in the high index core **104**.

A tapered region **108** of length L_1 on core material **102** is provided at one end of the low index difference waveguide. This taper **108**, shown in FIG. 6, decreases in width as one moves toward the untapered portion of core material **104** (that is, from left to right in FIG. 6). A tapered region **110** of length L_2 on core material **104** is provided at one end of the high index difference waveguide. This taper **110** decreases in width as one moves toward the untapered portion of core material **102** (that is, from right to left in FIG. 6). These tapered regions **108**, **110** are configured to intertwine so that a portion **112** of length L_3 of the tapered region **110** is embedded within the tapered region **108**. FIG. 7 is a side view of mode transformer **100** that shows the portion **112** of length L_3 . In the embodiment depicted in FIGS. 6 and 7, the tapered regions **108**, **110** are tapered only in the horizontal direction. In the top view of FIG. 6, for instance, the widths (that is, from top to bottom as viewed) of tapered regions **108**, **110** vary with lateral distance (that is, from left to right as viewed). The side view of FIG. 7, therefore, shows that the cores **102**, **104** are not tapered in the vertical direction (that is, from top to bottom as viewed). FIG. 7 shows, however, that the vertical width of core material **102** is greater than the vertical width of core material **104**. The portion **112** of core material **104** of length L_3 that is embedded in core material **102** is therefore surrounded on all sides by core material **102**. FIG. 8, which is a cross-section of FIG. 7 in the portion **112** of length L_3 , shows that the tapered portion **110** of core material **104** is surrounded on all sides by the tapered portion **108** of core material **102**.

Although FIGS. 6 and 7 show tapers **108**, **110** in only the horizontal direction, in other embodiments of the mode transformer **100** the tapers **108**, **110** can be tapered in the vertical direction as well, e.g., pyramidal or cone-like in shape. In such embodiments, the taper **108** of the high index core **104** would form a point within the embedded portion **112**, and the taper **110** of the low index core **102** would also be tapered in the vertical direction. The side view of FIG. 2 could therefore look more similar to the view of FIG. 6 in such an embodiment. In other embodiments, each taper **108**, **110** can have a tip that is not pointed, but instead has a discernable width that is smaller than the respective core material **102**, **104**, i.e., it is blunted or rounded. In other embodiments, multiple tapers **108**, **110**, or “fingers,” can protrude from cores **102**, **104**, rather than a single taper **108** on core **102** and a single taper **110** on core **104**. These fingers can intertwine to cause a gradual change in effective index and mode similar to that caused by the dual tapers **108**, **110** of FIGS. 6 and 7. In still other embodiments, the cross-sectional shape of the high index core material **104** and low index core material **102** can be modified to match the shape of external optical fiber on the low index side of the transformer **100** and to match the shape of the high index waveguide used for optical functions on the high index side of the transformer **100**.

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The index of refraction n_2 of the core material **104** is larger than the index of refraction n_1 of the core material **102**, which is, in turn, larger than the index of refraction n_3 of the cladding material **106**. In the illustrated exemplary embodiment, n_1 is slightly larger than n_3 . The low index difference waveguide defined by the core material **102** and cladding material **106** (seen in cross-section in FIG. 9) has a small index difference Δn , since n_1 is only slightly larger than n_3 :

$$0 < \frac{n_1 - n_3}{n_3} < 0.1.$$

On the other hand, the high index difference waveguide defined by the core material **104** and cladding material **106** (seen in cross-section in FIG. 10) has a larger index difference Δn , since n_2 is much larger than n_3 :

$$0.1 \leq \frac{n_2 - n_3}{n_3}.$$

FIG. 9 shows a cross-sectional view of the mode transformer **100** of FIGS. 6 and 7 in the untapered portion of core material **102**. The mode field size of an input optical fiber or low index difference waveguide has a cross-sectional dimension similar to that shown in FIG. 9. Such an input optical fiber can be coupled to the left side of the mode transformer **100** as shown in FIGS. 6 and 2 when the mode transformer **100** is used to couple optical fiber to a high index difference waveguide. When used in the optical chip of FIG. 2, the low index difference waveguide **22** can be coupled to the left side of the mode transformer **100**. FIG. 10 shows a cross-sectional view of the mode transformer **100** in the untapered portion of core material **104**. The mode field size of a high index difference waveguide that can be coupled to the right side of mode transformer **100** has a cross-sectional dimension similar to that shown in FIG. 10. When used in the optical chip of FIG. 2, the high index difference waveguide **24** can be coupled to the right side of the mode transformer **100**.

In operation, the mode of propagating lightwaves traveling from left to right in the mode transformer **100** as shown in FIG. 6 will be transformed from the mode of the low index difference waveguide, whose core/cladding indices are n_1/n_3 , to the mode of the high index difference waveguide, whose core/cladding indices are n_2/n_3 .

The mode entering the mode transformer **100** on the left side of FIG. 6 is defined by the low index difference waveguide cross-section shown in FIG. 9. In one embodiment, such as that shown in FIG. 9, this mode is that defined by a low index difference channel waveguide. The optical mode is guided by the low index difference waveguide, preserving the mode characteristics of the low index difference waveguide until the taper **110** of the high index core **104** is introduced into the low index core **102**. In taper **110**, the high index core **104** is horizontally tapered to gradually change the effective index of refraction from that of the low index difference waveguide to that of the high index difference waveguide. The “effective index” is an effective index of refraction, or average refractive index, calculated for the entire cross-section of a waveguide, which can include more than one distinct layer of material. Such an effective index determines the mode field of light in a waveguide. When the high index core **104** is narrow in taper **108**, the effective index is close to the index of refraction n_1 of the low index core **102** (and the cladding **106**). The mode properties at this point are therefore also similar to the mode

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properties of the low index high index core **104** at this point. As the high index core **104** is gradually widened, the effective index increases accordingly, approaching the index of refraction n_2 of the high index difference waveguide. The mode gradually transforms into a mode defined by the waveguide cross-section shown in FIG. 10 for the high index difference waveguide. As the effective index varies, therefore, the mode of propagating lightwaves varies accordingly. In one embodiment, the mode for the cross-section of FIG. 10 is that defined by a high index difference channel waveguide.

The core material **102** is tapered in the opposite direction from the core material **104**, as seen in FIG. 6. This taper **108** terminates the low index difference waveguide once the mode is coupled into the high index difference waveguide. This taper **108** also enhances the efficiency of the mode transformation by optimizing the focusing and reflection of the mode. Taper **108**, for instance, assists in focussing light into the high index core material **104** by reflecting light toward core **104**. Because the core **102** of the low index difference waveguide is large and the index difference Δn between the core **102** and the cladding **106** is small, the focussing effect of the taper **108** dominates over the change in mode size at this point in the waveguide. Before the point where the taper **110** of the high index core **104** is introduced into the taper **108**, for instance, the taper **108** causes the effective index to decrease slightly, which could increase the mode size. This slight decrease in the effective index, however, is dominated by the focussing effect of the taper **108**. The taper **108** therefore focuses light into the high index core **104**, which increases the efficiency of the transformer **100**. The shape of taper **108** inherently reduces the back-reflection.

The tapered region **108** of the low index difference waveguide and tapered region **110** of the high index difference waveguide provide an efficient, bi-directional mode transformer **100**. The taper **110** of the high index difference waveguide terminates the high index difference waveguide once the mode is coupled into that of the low index difference waveguide, and vice versa. The mode transformer **100** works for light traveling from right to left as well as from left to right as shown in FIGS. 6 and 7, making it a bi-directional mode transformer.

The taper length L_2 of the high index core **104** can be designed to minimize mode transformation loss. In other words, this length L_2 is designed to slowly change the mode (and the effective index) from that of the low index difference waveguide to that of the high index difference waveguide. The design of the taper **108** of the low index core **102** can be designed to minimize reflection, maximize focusing, and maximize efficiency. The taper **108** of the low index core **102** can, for instance, assist in focussing light into the mode of the high difference wavelength. The embedded portion **112** of the tapered regions **108**, **110**, can also be chosen to maximize coupling efficiency.

The mode transformer **100** is useful for coupling the mode from an optical fiber to a high index difference waveguide. The optical fiber can be coupled on the left side of the transformer **100** as shown in FIG. 6. The cross-section of typical optical fiber can have a profile similar to the cross-sectional view of the left side of the transformer **100** shown in FIG. 9. The index difference Δn between the core material **102** and cladding material **106** can be chosen to be similar to that of fiber (~ 0.01). The core/cladding indices n_1 , n_3 and thus the mode are similar to that of optical fiber, resulting in a highly efficient coupling to such optical fiber. Once the mode is coupled with optical fiber, the mode will be trans-

formed by transformer **100** into the mode of a high index difference waveguide as described above.

This coupling technology can be applied to any system coupling a low index difference waveguide to a high index difference waveguide. One can use SiO_2 as the cladding material **106**, SiO_xN_y as the low index difference waveguide core material **102**, and Si_3N_4 as the high index difference waveguide core material **104**. These materials can vary in different embodiments. For the illustrated exemplary embodiment, the low index core **102** has a $10\ \mu\text{m}$ by $10\ \mu\text{m}$ square dimension, the high index core has a $1\ \mu\text{m}$ by $1\ \mu\text{m}$ square dimension, $L_1=L_2=50\ \mu\text{m}$, and $L_3=40\ \mu\text{m}$. In addition, the tapers **108**, **110** are linear tapers. These dimensions can vary in other embodiments. This design produces a simulated value of 75 percent efficiency at a light wavelength of $1.55\ \mu\text{m}$. This is an improvement of over 30 percent efficiency over the case of butt-coupling a low index core to a high index core without a dual-taper. The transformer **100** is also a bi-directional transformer, which shows similar efficiencies for mode transformation in both directions.

The embodiment of the transformer **100** described above can be made in a variety of ways. For example, the transformer **100** can be formed by lithographic techniques. Such a process can involve depositing a layer of material and then etching away portions of that material that are not desired. This process of depositing material and etching away undesired portions can be repeated until the transformer **100** is formed. Tapered edges can be formed through patterning a layer of material through the use of a mask. After deposition of a layer of material, portions of the material can be irradiated through the mask so that the tapered portions are etched into desired shapes. To form the embedded portion **112** (FIG. 7) of the high index core **104** within the low index core **102**, a layer of Si_3N_4 as high index core **104** can be deposited and etched to form the taper **110**, and then subsequent layers of SiO_xN_y as low index core **102** can be deposited and etched around the taper **110** to form the taper **108** in the low index core **102**. SiO_2 for cladding material **106** can be deposited in appropriate layers to complete the fabrication of the transformer **100**.

The fabrication method described above involves a number of deposition and etching steps to form different portions of the taper **108** in the low index core **102** and to form the taper **110** in the high index core **104**. In another fabrication method, the high index core material **104** can be deposited and etched to form the taper **110**, and then a layer of low index photosensitive material can be deposited around the taper **110**, followed by deposition of the cladding material. The low index photosensitive material can be selected so that the index of refraction of this material, before being altered through exposure to light, matches the index of refraction of the material used for the cladding region. A mask can then be fabricated to cover portions of the low index photosensitive material that are to keep the same index of refraction as the cladding material, and thus become part of the cladding regions. The index of refraction changes for portions of the low index photosensitive material that are not covered by the mask and are instead exposed to light. These portions of the low index photosensitive material therefore become the low index core **102**, including the tapered portion **108** of the low index core **102** when the mask is appropriately shaped. Such a fabrication technique reduces the number of deposition and etching steps that are necessary to form the transformer **100**. A low index photosensitive material that reduces or increases its refractive index when exposed to energy can also be used. In this case, the portion

of the layer that becomes cladding can be masked either positively or negatively to create the appropriate structure.

While exemplary embodiments of the transformer **100** have been illustrated with continuous or linear (flat edged) tapers, it will be appreciated that segmented or non-linear tapers can also be utilized in accordance with the invention. For example, the tapers can have stepped tapered edges, or a concave or convex shaped tapered edges.

FIG. **11A** is a cross-sectional view of the waveguide of either FIG. **9** or **10**. FIGS. **11B–11I** are some possible index profiles along line **5–5** in FIG. **11A**. These index profiles show the index of refraction change with horizontal or vertical direction change, and these index profiles can be for the interface between a low index core and cladding material or between a high index core and cladding material. While exemplary embodiments have been illustrated with step index difference waveguides shown in FIGS. **11A** and **11B**, it will be appreciated that other index profiles between the core and the cladding can also be utilized.

For example, various other index profiles such as graded index and step graded index profiles can be used as long as the refractive index of the core material is higher than the refractive index of the cladding material on average. Such profiles are shown in FIGS. **11C–11I**. The various index profiles in FIGS. **11B–11I** are illustrated along the horizontal (or vertical) direction for purposes of illustration, but can also be applied in other directions.

While exemplary embodiments of the transformer **100** have been illustrated with the second taper **110** embedded in the first taper **108**, it will be appreciated that two tapers whose tips are optically in contact can also be utilized. In such an embodiment, one of the cores is not embedded within the other core. Instead, the tips of each taper can be physically in contact or, in other embodiments, the tips can be physically separated, but remain optically in contact. An example of two tapers **108**, **110** whose tips are considered to be optically in contact is shown in FIG. **12**. When the distance D between the tips of the two tapers **108**, **110** shown in FIG. **12** is short enough to allow for appreciable transmission efficiency, the tapers **108**, **110** are considered to be optically in contact, even though the tapers have no overlapping sections or embedded portions, and even though the tips of the tapers **108**, **110** are physically separated. In exemplary embodiments, D is less than or equal to 3λ , where λ is the wavelength of light propagating along the waveguide. Appreciable transmission efficiency is defined as efficiency higher than or equal to 1–10 percent.

While exemplary embodiments of the transformer **100** have been illustrated with two channel waveguides, it will be appreciated that other waveguide configurations can be used as long as the mode-field sizes in cross-sectional area are similar to those in the channel waveguides used in the illustrated embodiments.

FIGS. **21–27** are simplified schematic diagrams of an exemplary embodiment of a second mode transformer or coupler that can be used in accordance with the invention. Such a mode transformer or coupler can be used as the coupler **100** on substrate **20** (FIGS. **2–5**) to optically couple the large mode size waveguide **22** to the low minimum bending radius waveguide **24**, although such a coupler can be used for other coupling applications as well. In the embodiments of this coupler or mode transformer described below, the large mode size waveguide **22** is a low index difference waveguide, and the low minimum bending radius waveguide **24** is a high index difference waveguide **24**, although, as mentioned above, other low minimum bending radius waveguides or large mode size waveguides can be used in other embodiments.

FIG. 21 is a three dimensional view of one embodiment of this mode transformer. The core 1103 of the high index difference waveguide is completely embedded inside the core 1101 of the low index difference waveguide. The low index difference waveguide end of the mode converter has a large mode size, so that when coupled to an external device, such as an optical fiber or another large mode size waveguide, the connection loss is small. The high index difference waveguide core 1103 has a tapered end (taper 1108) that is embedded inside the core 1101 of the low index difference waveguide as seen in FIG. 21. The taper 1108 can be continuous or linear, or segmented or non-linear. The low index difference waveguide is formed by the low index core 1101 surrounded by a cladding 1102. The low index difference waveguide core 1101 becomes a cladding to the high index difference waveguide core 1103 because the low index difference waveguide core 1101 has a lower refractive index than the high index difference waveguide core 1103.

The taper 1108 in the high index difference waveguide core 1103 helps achieve a gradual change in the effective index from the low index difference waveguide on the left to the high index difference waveguide on the right. The light traveling in the right direction (as viewed in FIG. 21) through the low index difference waveguide goes through a mode transformation from that of a low index difference waveguide to that of the high index difference waveguide. The core 1101 of the low index difference waveguide becomes a cladding to the high index difference waveguide core 1103, because the low index difference core 1101 completely surrounds the high index difference waveguide core 1103. The core/cladding interface (1101/1102) for the low index difference waveguide virtually has no impact on the mode propagation in the high index difference waveguide core 1103 because the high index difference waveguide is a highly confining waveguide and the evanescent field does not extend far enough toward the core/cladding interface (1101/1102) of the low index difference waveguide.

The core 1101 of the low index difference waveguide tapers out (that is, away from the high index core 1103 in at least one plane) once the light is coupled into the high index difference waveguide core 1103, as light travels from left to right in FIG. 21. This outward taper is denoted by numeral 1107 in FIG. 21. The core 1101 can taper out to become a slab waveguide region 1106, which embeds one or more high index difference waveguide cores, which are shown in FIG. 21 as three cores 1103, 1104, 1105 for illustration purposes. The core 1101 can also taper out (1107) to become a waveguide with a larger width. For example, if the low index difference waveguide on the left is a single-mode waveguide, it can become a multi-mode waveguide whose core is larger than that of a single-mode waveguide. The high index difference waveguide core will then be completely immersed in the core of this larger waveguide. By tapering out (1107) the low index difference waveguide in the presence of the high index difference waveguide, the lateral confinement in the low index difference waveguide is removed and the low index difference waveguide core 1101 becomes one big cladding region (slab waveguide region 1106) for the high index difference waveguide cores 1103, 1104, 1105, as seen in FIG. 21.

Inside the slab region 1106 provided by the low index difference waveguide core, devices based on high index difference waveguides can be built by embedding the high index difference cores 1103, 1104, 1105. The slab region 1106 does not have to be of the same thickness throughout the entire region because the thickness of this slab is not

critical to the operation of the mode converter. Beyond the mode converter portion the slab region 1106 only has to be thick enough to act as a cladding to the high index waveguide cores 1103, 1104, 1105, which can be much thinner than the cladding 1102 for the low index waveguide core 1101.

FIG. 22 is a top view of one of the mode converters of FIG. 21. The core/cladding interface 1101/1102 of the low index difference waveguide forms a channel waveguide on the left. Once the light is coupled into the high index difference waveguide core 1103, the core 1101 of the low index difference waveguide tapers out (1107) to become a slab waveguide 1204, therefore removing the lateral cladding region 1102. The taper 1108 in the high index difference waveguide core 1103 helps gradually transform the mode with low loss.

FIG. 23 is a side view of one of the mode converters of FIG. 21—a cross section along line A—A in FIG. 21. The high index difference waveguide core 1105 is completely embedded inside the low index difference waveguide core 1011 throughout the mode transformation. The low index difference waveguide core 1011 is sandwiched between the undercladding 1202 and the uppercladding 1203. A substrate 305 can be used for mechanical support. The low index difference waveguide core 1011 and cladding 1202, 1203 is shown as flat for illustration purposes only. In fact, in the region where the high index difference core 1105 is embedded in the low index difference core 1011, the interfaces 1011/1202, 1011/1203, and 1202/305 need not be flat and may be curved, sloped or stepped.

FIG. 24 shows a cross-sectional view along line B—B in FIG. 21. The high index difference waveguide core 1105 is completely embedded inside the low index difference waveguide core 1011 throughout the mode transformation area. The low index difference waveguide core 1011 is surrounded by the cladding 1102. A substrate 305 can be used for mechanical support. The high index core 1105 in the embodiment shown in FIG. 24 is at or near the center of the low index core 1011 in order to achieve optimal mode transformation efficiency. Placing the high index core 1105 at or near the center of the larger low index core 1011 results in some portion of low index core 1011 being below the high index core 1105 and some portion of the low index core 1011 being above the high index core 1105.

FIG. 25 shows a top view showing multiple mode converters of the type shown in FIG. 21. The low index difference waveguide cores 501, 502 taper out and connect to a single slab region 509 which contains the high index difference waveguide cores 507, 508. Regions 503, 504, 505 are cladding regions for the low index difference waveguide cores 501, 502.

FIG. 26 shows a top view of a variation of the design of the low index difference waveguide taper of FIG. 21. The low index difference waveguide core 601 first tapers in (at taper 602) to optimize the mode conversion efficiency from the low index difference waveguide core 601 to the high index difference waveguide core 607. The low index difference waveguide core 601 then tapers out (at taper 603) to a slab waveguide 604. The core 607 of the high index difference waveguide tapers to become smaller toward the left (taper 610) so that the taper 610 of the high index difference waveguide core 607 is within the taper 602 of the low index difference waveguide core 601.

In FIG. 21, the index of refraction of the high index difference core 1103, n_2 , is larger than n_1 and n_3 , the indices of the low index difference core 1101 and the cladding 1102. In the illustrated exemplary embodiment, n_1 is slightly larger

than n_3 . The low index difference waveguide is defined by the core **1101** and cladding **1102** as seen in FIG. **21**, since n_1 is only slightly larger than n_3 :

$$0 < \frac{n_1 - n_3}{n_3} \ll 1.$$

On the other hand, the high index difference waveguide is defined by the core **1103** and cladding **1101** as seen in FIG. **21**, since n_2 is much larger than

$$0 < \frac{n_1 - n_3}{n_3} < \frac{n_2 - n_1}{n_3}.$$

The optical fiber, which has a cross-sectional dimension that is similar to that of the low index difference waveguide shown on the left side of FIG. **21**, is coupled to the left side of the mode converter **100**.

In operation, the mode traveling from left to right in the mode converter **100** as shown in FIG. **21** will be transformed from that of the low index difference waveguide, whose core/cladding indices are n_1/n_3 , to that of the high index difference waveguide, whose core/cladding indices are n_2/n_1 .

The mode entering the mode converter on the left side of FIG. **21** is guided by the low index difference waveguide, preserving the mode characteristics until the taper **1108** in the high index core **1103** is introduced, as shown in FIG. **21**. In taper **1108**, the core **1103** is horizontally tapered to gradually change the effective index from that of the waveguide mode in the low index waveguide. When the core **1103** is narrow in taper **1108**, the effective index is close to that of the low index difference core **1101**, and thus the mode properties are similar. As the core **1103** is gradually widened as one moves toward the right, the effective index increases accordingly, approaching that of the high index difference waveguide. The mode gradually transforms into a mode in the high index difference waveguide **1103** by the change of the effective index.

The core **1101** is tapered out (at taper **1107**) to a slab region **1106**. This taper **1107** of the low index difference waveguide is present once the mode is coupled into the high index difference waveguide. This taper **1107** can also ensure that the high index difference waveguide core **1103** is completely embedded in a single material system for ease of manufacturing compared to other mode converter designs where cladding to the high index difference core is composed of several different materials.

The taper in the low index difference waveguide core can have various designs to optimize the mode conversion efficiency. For example, this taper can first taper down as in taper **602** in FIG. **26** to maximize mode conversion efficiency before it flares out (taper **603**) to a slab region **604**. The design of taper **602** can also be optimized to suppress the excitation of higher order slab modes in **1204** (FIG. **22**), **509** (FIG. **25**), and **604** (FIG. **26**) that may cause increased noise at the output and reduce the ability of the mode converter to be bi-directional. Alternatively, absorbing or scattering regions or interfaces can be used to suppress the propagation of these modes through the slab.

The taper length of the high index difference core can be designed to minimize mode transformation loss. The design of the taper in the low index core can be designed to minimize reflection, maximize focusing, and maximize efficiency.

The mode converter of FIGS. **21–27** is useful for coupling modes between an optical fiber and a high index difference

waveguide. The fiber mode can be coupled on the left side of the converter as shown in FIG. **21**. The index difference between the low index difference core **1101** and cladding **1102** can be chosen to be similar to that of optical fiber (~0.01). The core/cladding indices and thus the mode are similar to that of optical fiber, resulting in a highly efficient coupling using methods that will be known to a person skilled in the art. Once coupled, the mode will be transformed into that of a high index difference waveguide as described above.

The embodiment of FIGS. **21–27** is also useful to couple optical waveguides on different substrates with different index contrast waveguides efficiently. In this case, the mode converter would be included on one of the two substrates, thereby allowing mode field size matched coupling between the two substrates.

The mode converter presented in FIGS. **21–27** can also be used to connect waveguides with different index contrasts which are fabricated on the same substrate. For example, optical devices with ring resonators may require a different index difference than optical amplifiers. These optical devices utilizing various index difference waveguides could all be fabricated and coupled efficiently on the same chip.

The mode converter shown in FIGS. **21–27** is bi-directional and works with similar efficiency if the low index difference waveguide output and the high index difference waveguide output are single-moded. Therefore, light in the high index difference waveguide can be coupled into the low index waveguide, and optionally, into an optical fiber by reversing the path of the light. In FIG. **21**, light in waveguide **1103** that is traveling from right to left will be coupled to waveguide **1101** through mode conversion. The taper **1108** is designed to cause a decrease in the effective index of the core **1103** of the high index difference waveguide so that the effective index of the narrowest point of taper **1108** will match or almost match the effective index of waveguide **1101**. The light that is coupled into waveguide **1101** can then be matched to that of an external optical fiber which is butt coupled to this waveguide.

The design of this mode converter can optionally be optimized to suit different fabrication and integration requirements. In one such design, the core (for example, core **1101** of FIG. **21**) of the slab region (see, for example, **1106**) may be reduced in thickness in locations which are more than several wavelengths away from the high index tapers (for example **1108**). In this case, there will be a step in the interface between the under-cladding **1202** and the substrate **305** (see FIG. **23**). This step will not cause any increased optical loss. This additional feature does not fundamentally change the operation of the mode converter but allows for increased flexibility for integration with other optical devices, such as detectors. As a general rule, the design of the mode converter is not critically dependent on the continuity of the slab region.

This mode converter technology of FIGS. **21–27** can be applied to any high index difference waveguide system. For example, one can use undoped or doped silica (SiO_2) or silicon oxynitride (SiON) as the cladding, SiON as the low index difference waveguide core, and silicon nitride (Si_3N_4) as the high index difference waveguide core. Silicon oxynitride or silicon-rich silicon nitride can also be used as the high index difference waveguide core. One can also use undoped SiO_2 or Ge or phosphorous doped SiO_2 as the low index difference waveguide core instead of SiON . One can also use silica (SiO_2) as the low index difference waveguide core and use doped silica as the cladding whose index is lower than that of the low index difference waveguide core.

Another example of a set of materials which may be used is SiO₂ as the cladding, doped SiO₂ as the low index difference waveguide core, and Si as the high index difference waveguide core, where the dopant or dopants of the SiO₂ may be Ge, B, F, P or N. Another exemplary materials system is the III-V system where light in a low index difference semiconductor waveguide can be coupled to and from a high index difference waveguide using an appropriate choice of materials.

FIGS. 27A–27E show an example of fabricating the invention using the cross-section along line B—B in FIG. 21. In FIG. 27A, the lower portion of the low index difference waveguide core layer 703 is built on the low index difference waveguide cladding 702 layer, which is in turn on a substrate 701 for a mechanical support. The patterned high index difference waveguide core 704 is located on top of the low index core layer 703. The high index difference waveguide core 704 can be first created as an unpatterned layer by deposition or a wafer-bonding process. Then this layer can be patterned into the shape of high index difference waveguide core 704 by conventional photo-lithography and etching processes. Subsequently, the upper portion of the low index difference waveguide core 705 is deposited on top of the patterned high index difference core 704, as shown in FIG. 27B. If the deposition of the low index difference waveguide core 705 is conformal, a chemo-mechanical polishing (CMP) can be applied to it to planarize this layer. High temperature reflow can also be applied for planarization, as depicted in FIG. 27C. However, the planarization process may not be necessary depending on the specific functional needs. In FIG. 27D, the low index difference waveguide core 705 and low index core layer 703 are patterned. Finally, as shown in FIG. 27E, the upper cladding 706 is deposited on top.

Typically the low index core layer 703 is patterned in a way that the high index difference core 704 is completely embedded inside the low index core layer 703 even after the etching process of the low index core layer 703. However, one can choose to etch the low index core layer 703 so that some portion of the high index difference core 704 is not embedded in the low index core layer 703. The subsequent deposition of cladding 706 will provide the core/cladding interface between the high index difference core 704 and cladding 706 in the portion of the high index difference core 704 that is not embedded in the low index core layer 703, 705. This core/cladding interface of the high index difference core 704 and cladding 706 is similar to the interface between the high index difference core 704 and the low index core layer 703, 705 that exists where the high index difference core 704 is embedded in the low index core layer 703, 705. There will be a minimal impact on the optical performance of the device if the high index difference core 704 is not completely embedded in the low index core layer 703, 705 because the refractive indices of the low index core layer 703, 705 and the cladding 706 are close to each other, particularly when compared to the refractive index of the high index difference core 704. For example, one can easily make an embodiment such that one or both sidewalls of the low index core layer 703, 705 in FIG. 27D coincides with a sidewall of the high index core 704 by the design and fabrication of the low index core 705, 705.

An alternative fabrication method involves using photo-sensitive materials for the core of the low index waveguide 705 and 703 (FIGS. 27A and 27B). Again the planarization step is preferred but optional. In this case, no etch is performed but the core of the low index waveguide is defined by selective exposure of layers 705 and 703 to an

electromagnetic energy (light energy). This energy is selectively exposed to these layers to increase the index of the core of the waveguide relative to the cladding 706. Alternatively, one can use exposure of light energy to the cladding region if it reduces the index with respect to the core region.

While exemplary embodiments of the invention have been illustrated with continuous or linear (flat edged) tapers, it will be appreciated that segmented or non-linear tapers can also be utilized in accordance with the invention. For example, the taper can have a stepped taper edge, or a concave or convex shaped taper edge.

High index difference waveguides, such as those having an index difference Δn of at least 0.1 that are used in the transformer 100 and optical chips described above, can cause large scattering losses for propagating light. Light striking the interface between core material and cladding material can be scattered due to imperfections or roughness at the interface. Thus, edges with rough interfaces can be prone to cause scattering losses. High index difference waveguides typically have a smaller core diameter than low index difference waveguides. Light therefore strikes the interface between the core material and the cladding material with greater frequency for high index difference waveguides than for low index difference waveguides, resulting in greater scattering losses. In addition, scattering losses increase as the index difference between the core material and the cladding material increases.

The high index difference waveguides used on substrate 20, within transformer 100, and within optical chips described herein can be created to reduce or suppress sidewall scattering losses.

In one embodiment, a separate graded index region can be applied over a high index core material and between the high index core material and cladding material to decrease scattering losses. FIG. 13 is a cross-sectional view of an exemplary embodiment of a graded index planar waveguide 200. Such a waveguide 200 can be a low minimum bending radius waveguide used on an optical chip or a transformer 100 as described above. One example of such a low minimum bending radius waveguide, which is shown in FIG. 13, is a high index difference waveguide. The waveguide 200 of FIG. 13 includes a substrate 205 for mechanical support (this can be substrate 20 of FIGS. 2–5), a first low index cladding 204, a high index core 201, a graded index region 203, and a second low index cladding 202. The refractive index n_1 of the core 201 is larger than the refractive indices n_2, n_4 of the cladding regions 202, 204. Cladding region 202 can, in one embodiment, be made from the same material as cladding region 204. In other embodiments, these cladding regions 202, 204 can be made from different materials and can have different indices of refraction. The graded index region 203 is a separate, unique region between the core 201 and the cladding 202. The index of refraction of the graded index region 203 gradually varies from that of the high index core 201 to that of the low index cladding 202, 204. Scattering of light due to the rough interfaces between the core 201 and the cladding 202 is minimized because the index change from core 201 to cladding 202 is gradual due to the graded index region 203.

FIG. 13 depicts a layer of the graded index region 203 deposited over the high index core 201 on three sides. A fourth side 210 of the high index core 201 is not covered by the graded index region 203. An additional graded index region can, however, be applied between the core 201 and the cladding 204 on side 210 if the interface between the core 201 and the cladding 204 is rough. This layer will also

make the waveguide look more symmetric, reducing polarization dispersion.

In other embodiments, the graded index region **203** can be applied to one, two, or all sides of the high index core **201**. In still other embodiments, the high index core **201** can have a different cross-section than the rectangular cross-section shown in FIG. **13**. In such embodiments, the graded index region **203** can be applied to a portion of the edge of the high index core **201** or all around the high index core **201**. Generally, portions of the edges of the high index core **201** are rough from the fabrication methods used to create the high index core **201**. It can be desirable, in some embodiments, to apply the graded index region **203** to these rough edges. Rough edges cause greater scattering losses than smooth edges, so it can, in some embodiments, be less important to apply the graded index region **203** to the smooth edges.

For the embodiment shown in FIG. **13**, the side edges **212**, **214** of the high index core **201** can have rougher surfaces than the other edges due to the fabrication technique of the high index core. Etching processes, for example, can be used to form the side edges **212**, **214**, and these side edges **212**, **214** can therefore be rough. In one embodiment, therefore, a graded index region **203** is applied to only these side edges **212**, **214** of the high index core **201**. In this embodiment, therefore, low index cladding **202** abuts the top of the high index core **201** (not shown in FIG. **13**), low index cladding **204** abuts the bottom **210** of the high index core **201**, and the graded index region **203** is between the high index core **201** and the low index cladding **202** on side edges **212**, **214**.

The index cross-section of the high index core **201**, cladding **202**, and the graded index region **203** for the embodiment of FIG. **13** is demonstrated in the graph of FIG. **14**. The index profile of the graded index region need not be linear, as shown in FIG. **14**. The refractive index in the high index core **201** is higher than that in the cladding **202**. The refractive index in the graded index region **203** is graded so that there is a less abrupt jump in refractive index between the high index core **201** and cladding **202**. The refractive index of the graded index region **203** can be changed between low and high refractive index regions using any index profiles such as curves and staircase steps. Any profile that reduces the index jump from core **201** to cladding **202** at the interface will lower the scattering loss. The graded index region **203** can be designed so that the loss is optimally minimized. At the same time, the design of the graded index region **203** can address the change in the confinement factor (that is, how tightly light is confined in the waveguide core **201**) due to the presence of the graded index region **203**. The graded index region **203** will play a role in waveguide performance, including in areas such as bends in the waveguide. The design of the graded index region **203** can also reduce modal and polarization dispersion.

FIG. **15** is a diagram of an exemplary fabrication process of a graded index waveguide in accordance with the invention. The low index cladding **204** is deposited with the high index core **201** deposited over the cladding **204**. The patterned waveguide core **201** has rough edges **212**, **214** arising from the patterning techniques used. Thereafter, the graded index region **203** is deposited over the core **201**. During the deposition process, the index of the layer is varied from that of core **201** to that of cladding **202**. The index grading can be achieved by varying the chemical composition of the layer. Finally, the cladding region **202** is deposited on top.

Such a gradient in the refractive index of the graded index region **203** can also be obtained by a thin film growth method. During the growth process, the composition of the

impinging material at the waveguide core surface can be changed to obtain an index gradient.

Another method of making graded index region **203** in the waveguide is to obtain a gradient in the atomic composition at the surface of the waveguide core **201** from a chemical reaction. The composition of the waveguide core **201** can be altered by chemical reactions that yield products that are transparent to the wavelength of interest and that have an index lower than that of the core **201**. Since the concentration of the reactant of the chemical reactions is highest at the surface and decreases exponentially due to the diffusion of the reactant into the core material, there will be a concentration gradient of the product into the core material starting from the surface. The index near the surface will be graded according to the chemical composition gradient.

A graded index silicon nitride waveguide is an example of this type of waveguide. As shown in FIG. **13**, the graded index region **203** in this case is a silicon oxynitride layer whose refractive index varies from that of a silicon nitride core **201** to that of a silicon dioxide cladding **202**. The index change is achieved by changing the ratio of oxygen and nitrogen in the silicon oxynitride layer. Deposition techniques such as chemical vapor deposition or sputtering can be used for depositing this layer.

A graded index germanium(Ge)/silicon(Si) waveguide is an example of a graded index waveguide obtained by a thin film growth technique. When germanium is the core material **201** and silicon is the cladding material **202**, $\text{Si}_x\text{Ge}_{1-x}$ can be the graded index region **203**, and the refractive index of this graded index region **203** is graded during the growth process.

An example of obtaining a graded index region using a chemical reaction can be illustrated with a waveguide having a core **201** of silicon nitride and a cladding **202** of silicon dioxide. By subjecting the silicon nitride waveguide core **201** to oxidizing agents, a silicon oxynitride layer is formed at the surface. Since this process is controlled by diffusion of the oxidizing agents into the silicon nitride waveguide core **201**, the concentration gradient of oxygen and nitrogen is created at the surface, with the surface having the highest level of oxygen. The concentration of oxygen decreases into the waveguide core while that of nitrogen increases. The graded index region **203** is therefore formed between the core **201** and the cladding **202**.

In other embodiments of the invention, the rough surfaces of the waveguide are smoothed to reduce the root mean square (rms) roughness of the surface and thereby to reduce scattering losses. As noted above, waveguide patterning processes such as etching result in rough, uneven side edges. A low-loss waveguide is obtained by subjecting the patterned waveguide to treatments that smoothen the core/cladding interfaces, and/or change the waveguide core dimension. The method is particularly useful for low minimum bending radius waveguide systems where the scattering loss is high, in particular, where the waveguide will be bent to a small bending radius in the optical chip device. One example of such a low minimum bending radius waveguide is a high index difference waveguide. The method is useful for reducing scatter losses in single mode waveguides where the single mode cut-off dimension is less than about 2.5 times the wavelength in the core. In particular, the method can be used for waveguides having a mode size of less than 2 microns (μm).

In an exemplary embodiment, a method includes smoothening of the core/cladding interface of silicon-on-insulator (SOI)-based waveguides (Si/SiO_2) by oxidation of the core at high temperatures, after waveguide patterning. In other

exemplary embodiments, a method includes wet chemical etching of the waveguide core after waveguide patterning. In still other exemplary embodiments, a method includes annealing the waveguide in a gaseous ambient including hydrogen after waveguide patterning.

An exemplary embodiment of the invention provides an oxidation smoothing technique that reduces the roughness at the core/cladding interfaces of Si/SiO₂ (SOI) waveguide. FIG. 16 is a perspective block diagram of an initial SOI platform 1600 on which a silicon-containing waveguide is formed. In some embodiments, the waveguide is silicon or silicon nitride. A top silicon layer 1620 will be made into a waveguide core while a SiO₂ layer 1640 will become an undercladding region. The substrate 1660 can be made of any material, such as silicon, indium phosphide, ceramic, or quartz, and is provided for mechanical support.

FIG. 17 is a perspective block diagram of the platform including a waveguide core 1680 after a typical patterning process including photolithography and etching of the top silicon layer 1620 of FIG. 16. The sidewall roughness 1700 of the core 1680 is due to the waveguide patterning process. This roughness is responsible for scattering loss in the waveguide. The core 1680 is then subjected to oxidizing agents, such as O₂ or H₂O gases at an elevated temperature. The surfaces of the core will react with the oxidizing agents and form a coating layer of SiO₂ 1720, as shown in FIG. 18. Since convex points of the rough surface 1700 oxidize faster than concave points, the reaction tends to reduce the roughness of the core.

The reaction rate increases with the reaction temperature. When the reaction temperature is too low, oxidation does not proceed rapidly or extensively. When the reaction temperature is too high, one may not have a good control over the thickness of SiO₂ formed because of a high reaction rate. In order to grow nanometer (nm) to micron (μ m) thick layers of SiO₂ in a period of minutes to hours, typical reaction temperature ranges between 600 to 1200° C. The oxidation time will depend on the oxidation temperature since the reaction rate depends on the temperature.

In some embodiments, the oxidation time is chosen to achieve a desired waveguide core dimension. Since formation of oxidation product results in the consumption of the silicon waveguide core, initial core dimensions are chosen taking this factor into consideration. Thus, initial core dimensions are those that provide both a core of the desired dimension after the oxidation reaction has consumed a portion of the core. In some embodiments, oxidation conditions are selected to form an oxidation product that just reacts away surface roughness. The resultant oxidation layer is then removed and a suitable cladding is applied. In other embodiments, oxidation conditions are selected to provide an oxide layer that can serve as a cladding or portion of the cladding region in the final device, in which case no post fabrication of the waveguide is required because the final waveguide dimensions are obtained during the oxidation process. In still other embodiments, additional cladding material is deposited on the oxidation layer. The cladding material can be the same as or different from the oxidation layer.

Exemplary cladding materials include SiO₂, air and vacuum, alumina, organic polymers, and variations of silica such as spin-on glass, boron-phosphorus-doped silica glass (BPSG), phosphorus-doped silica glass (PSG), boron-doped silica glass (BSG), silicon nitride and silicon oxynitride (SiO_xN_y). FIG. 19 is a perspective block diagram of the platform following the removal of the SiO₂ layer 1720 to show the silicon core surface 1740 after smoothing. The rms

roughness value of the sidewalls can decrease several fold, e.g., by a factor of 2 to 5. Alternatively, one can choose not to remove the SiO₂ layer 1720 since it can act as a cladding layer for the waveguide core in FIG. 18.

Different oxidizing agents can be used to react with silicon to form SiO₂. Exemplary oxidizing agents include O₂, H₂/O₂, H₂O₂, ozone and the like. Suitable oxidizing agents are readily determined by the art skilled. The oxidation temperature and time should be chosen according to the chosen oxidant, since the reaction rate depends on the specific species of oxidants used.

The method of the invention can be used to smoothen the waveguide core surfaces of other geometries, such as ridge waveguides. Any SOI waveguide whose core is defined by a patterning process that produces surface roughness can be smoothened by this technique.

An experiment was carried out to demonstrate the oxidation smoothing of the waveguide sidewalls. To make Si/SiO₂ waveguides by oxidation smoothing, Ultrabond Si-on-insulator wafers with a 0.2 μ m-thick top Si layer on 1 μ m-thick SiO₂ were used. The wafers were patterned by photolithography and reactive ion etching (RIE) to obtain strip waveguides as shown in FIG. 17. For photolithography, a 10 \times stepper with a G-line UV lamp emitting at 436 nm was used. For RIE, SF₆ gas was used to etch the exposed Si. Straight waveguides of widths from 0.5 to 8 μ m were made. The waveguide then was subjected to a wet oxidation step for 43 min with H₂O and O₂ at 1000° C. After the oxidation step, the dimensions of the smallest waveguide were about 0.5 μ m in width and 0.05 μ m in height. The fabrication steps are shown in FIGS. 17–19, in which the resulting SiO₂ layer was removed to reveal the core/cladding interface for atomic force microscopy (AFM) analysis. A blanket layer of 1 μ m-thick SiO film was deposited by plasma-enhanced chemical-vapor deposition on the waveguides as an upper cladding layer for transmission loss determination.

The sidewalls of the waveguide fabricated by oxidation smoothing were viewed by AFM. The vertical roughness was distinctly different from that of the conventionally fabricated waveguide, which has an rms roughness of 10 nm and an autocorrelation length of 50 nm. In contrast, the rms sidewall roughness value for the oxidation smoothed sample was 2 nm for the same autocorrelation length. The oxidation reaction smoothen the roughness developed during the waveguide-patterning process (photolithography and RIE), since the convex points of the rough Si surface react faster than the concave points. The uneven reaction rates lead to a smooth Si surface, which is a lower surface-energy state.

During the experiment, the waveguide thickness decreased due to the consumption of silicon to form SiO₂. The reduction in thickness resulted in the reduction of the effective refractive index of the core, and thus in the reduction of the effective refractive index difference between the core and the cladding. The reduction in the effective refractive index difference between the core and the cladding resulted in additional reduction of the scattering loss since the scattering loss is a strong function of the refractive index difference between the core and the cladding.

Subjecting the already-fabricated waveguide core to a wet chemical etch smoothen the core/cladding interface also reduces the roughness and thus reduces transmission losses. Both anisotropic and isotropic etchants can be used. When an anisotropic etchant is used to smooth a single-crystalline core material, some or all of the core surfaces can become crystal planes, resulting in atomically smooth surfaces. Examples of anisotropic etchants for single-crystalline sili-

con core are KOH (Potassium Hydroxide) and TMAH (Tetra-Methyl-Amine-Hydroxide). When an isotropic etchant is used, the etching process reduces the roughness on the core surfaces to minimize the energy of rough surfaces. To make Si/SiO₂ waveguides by anisotropic etching, a 0.34 μm -thick (100) Si layer of a SOI wafer sitting on a 1 μm -thick SiO₂ layer was patterned to provide a 3 μm SiO layer on top of a 0.2 μm -thick Si core layer. With reference to FIG. 20, the top SiO₂ layer then was patterned by photolithography and RIE to make a hard mask for the core of the waveguides that were in the <110> direction. The sample was then immersed in a 25-wt. % aqueous solution of NH OH (TMAH) at 80° C. for 1 min, which was sufficient to completely etch away Si from the nonwaveguide area. TMAH was used as the anisotropic etchant because of its compatibility with complementary metal-oxide semiconductor (CMOS) processing with no metal ions. The oxide hard mask was removed afterward. A blanket layer of 1 μm -thick SiO₂ film was deposited by plasma-enhanced chemical-vapor deposition on the waveguides as an upper cladding layer.

The AFM image of the anisotropically smoothed waveguide shows a {111}-type atomic plane, developed during the etching process by TMAH because of its anisotropic etching ratios, which are dependent on crystal orientation. {111} planes are the slowest etching planes since they are the lowest-energy surfaces. Since the waveguides are aligned along the <110> direction on the (100) Si surface, {111} surfaces are revealed on the waveguide sidewalls, with the mask on the top waveguide surface. {111} surfaces coincide with the cleavage planes of a (100) Si wafer, which make an angle of 54.7 degrees with the (100) Si surface which is the angle that the sidewalls make with the top surface. The AFM image analysis leads to rms values of about 2 nm for the anisotropic etched sample.

Transmission losses were determined for both oxidation smoothing and anisotropic etching samples. Transmission losses at $\lambda=1.54$ nm were measured using cutback, IR capture of scattered light and Fabry-Perot resonance methods. The oxidation smoothed single mode waveguides exhibited scattering loss of less than 0.8 dB/cm, and compared very favorably to comparably sized waveguides with no oxidation smoothing, which exhibited losses of over 30 dB/cm. The anisotropically etched sample exhibited similarly low loss. The scattering loss rapidly increases as the waveguide width is reduced in conventionally processed waveguides because of the increased sidewall roughness scattering. Such an effect was effectively suppressed in the oxidation smoothed waveguides. The rms roughness values for the oxidation smoothed and anisotropically etched sidewalls were only one-fifth that of the conventionally fabricated waveguide.

While exemplary embodiments of the invention have been illustrated by subjecting the already-fabricated Si/SiO₂ waveguide core to the oxidation reaction to reduce the core/cladding interface roughness and by wet chemical etching of the core/cladding interface, it will be appreciated that annealing the already-fabricated Si/SiO₂ waveguide core in an gaseous ambient including hydrogen gases at elevated temperatures smoothens the core/cladding interface, and can also reduce the roughness and thus reduce losses. The silicon core material undergoes a diffusive process that tends to minimize the energy of the rough core surface, smoothing the rough core/cladding interface. Annealing is conducted at elevated temperatures, e.g., at about 100° C.

Any references to front and back, right and left, top and bottom, upper and lower, and horizontal and vertical are,

unless noted otherwise, intended for convenience of description, not to limit the present invention or its components to any one positional or spacial orientation. All dimensions of the components in the attached Figures can vary with a potential design and the intended use of an embodiment without departing from the scope of the invention.

While the present invention has been described with reference to several embodiments thereof, those skilled in the art will recognize various changes that may be made without departing from the spirit and scope of the claimed invention. Accordingly, the invention is not limited specifically to what is shown in the drawings and described in the specification.

What is claimed is:

1. An optical mode transformer, comprising:

a low index core;

a high index core having a first tapered region, wherein the high index core is embedded within the low index core and wherein the low index core serves as a cladding for a waveguide defined by the high index core embedded in the low index core; and

a cladding layer surrounding the low index core, wherein the cladding layer is composed of one or more materials with different refractive indices than those of the low index core and high index core, wherein a first channel-like mode defined by the low index core and cladding layer gradually transforms into a second channel-like mode defined by the high index core embedded within the low index core,

wherein the low index core increases in dimension while embedding the high index core, wherein the dimension of the low index core is increased to a slab waveguide region that forms the cladding.

2. The optical mode transformer of claim 1, wherein the dimension of the low index core is increased to a multi-mode waveguide dimension.

3. The optical mode transformer of claim 1, wherein the low index core is connected to a slab waveguide.

4. The optical mode transformer of claim 1, wherein a first region of the optical mode transformer is the waveguide defined by the high index core embedded in the low index core and a second region is defined by the low index core not embedding the high index core.

5. The optical mode transformer of claim 4, wherein the first tapered region forms the beginning of the waveguide defined by the high index core embedded in the low index core, and wherein the low index core contains a taper forming a decreased dimension around the high index core in the beginning of the waveguide having the high index core, wherein the low index core increases in dimension after the taper to form the cladding.

6. The optical mode transformer of claim 4, wherein the first region is a high index difference waveguide and the second region forms a low index difference waveguide.

7. The optical mode transformer of claim 4, wherein the second region has a peak optical intensity at a position in the low index core, wherein the position of the peak optical intensity is defined in a cross-section perpendicular to a propagation direction of light.

8. The optical mode transformer of claim 7, wherein the first region has a peak optical intensity at a position in the high index core.

9. The optical mode transformer of claim 1, wherein the index of refraction of the low index core is relatively lower than the index of refraction of the high index core.

10. The optical mode transformer of claim 1, wherein the index of refraction of the low index core is slightly higher than the index of refraction of the cladding layer.

11. The optical mode transformer of claim 1, wherein the index of refraction of the high index core is substantially higher than the indices of refraction of the low index core and the cladding layer.

12. The optical mode transformer of claim 1, wherein a propagating optical mode is transformed in size, shape, and speed as it propagates between the low index core and the high index core.

13. The optical mode transformer of claim 1, wherein a propagating optical mode can propagate bi-directionally between the low index core and the high index core.

14. The optical mode transformer of claim 1, wherein a propagating optical mode can propagate bi-directionally between the low index core surrounded by the cladding layer and the high index core surrounded by the low index core.

15. The optical mode transformer of claim 1, wherein the first tapered region of the high index core provides an effective refractive index change to a propagating optical mode.

16. The optical mode transformer of claim 1, wherein the first tapered region of the high index core is continuous or linear.

17. The optical mode transformer of claim 1, wherein the first tapered region of the high index core is segmented or non-linear.

18. The optical mode transformer of claim 1, wherein the low index core and the high index core are made by a combination of layer creation and etching processes, wherein the layer creation process is one of a deposition process and a wafer-bonding process.

19. The optical mode transformer of claim 18, wherein a portion of the low index core is deposited before the layer creation and etching of the high index core and the remaining portion of the low index core is deposited after the layer creation and etching of the high index core.

20. The optical mode transformer of claim 18, wherein the low index core is patterned by etching after the layer creation and etching of the high index core.

21. The optical mode transformer of claim 1, wherein the high index core is made from a high refractive index material with a refractive index significantly higher than that of silica.

22. The optical mode transformer of claim 1, wherein the high index core is made from a nitrogen-containing compound.

23. The optical mode transformer of claim 22, wherein the nitrogen-containing compound is selected from Silicon Oxynitride, Silicon Nitride, and Silicon-rich Silicon nitride.

24. The optical mode transformer of claim 1, wherein the high index core is made from one of doped silica and Silicon.

25. The optical mode transformer of claim 1, wherein the low index core is made from one of undoped silica, doped silica, and silicon oxynitride.

26. The optical mode transformer of claim 1, wherein the cladding layer is made from one of undoped silica, doped silica, and silicon oxynitride.

27. An optical device, comprising:

two or more optical mode transformers, with each optical mode transformer comprising:

a low index core;

a high index core having a first tapered region, wherein the high index core is embedded within the low index core and wherein the low index core serves as a cladding for a waveguide defined by the high index core embedded in the low index core; and

a cladding layer surrounding the low index core, wherein the cladding layer is composed of one or more materials with different refractive indices than those of the low index core and high index core, wherein a first channel-like mode defined by the low index core and cladding layer gradually transforms into a second channel-like mode defined by the high index core embedded within the low index core, wherein two or more of the low index cores of the optical mode converters are connected to a single slab waveguide region that forms the cladding for the waveguides defined by the high index cores embedded in the low index cores.

28. The optical device of claim 27, wherein each optical mode transformer has a first region that is the waveguide defined by the high index core embedded in the low index core and a second region that is defined by the low index core not embedding the high index core.

29. The optical mode transformer of claim 28, wherein, for each optical mode transformer, the first tapered region forms the beginning of the waveguide defined by the high index core embedded in the low index core, and wherein the low index core contains a taper forming a decreased dimension around the high index core in the beginning of the waveguide having the high index core.

30. The optical device of claim 29, wherein, for each optical mode transformer, the low index core increases in dimension after the taper to form the cladding.

31. A dielectric waveguide optical mode transformer, comprising:

a first dielectric channel waveguide including a first core material surrounded by a cladding layer;

a second dielectric channel waveguide including a second core material having a first tapered region forming one end of the second dielectric channel waveguide, the second core material being embedded within the first core material, wherein the first core material tapers outward to increase in dimension and acts as a cladding for the second dielectric channel waveguide having the second core material,

wherein the dimension of the first core material is increased to a slab waveguide region that forms the cladding for the second dielectric channel waveguide.

32. The dielectric waveguide optical mode transformer of claim 31, wherein the first dielectric channel waveguide is a low index difference waveguide and the second dielectric channel waveguide is a high index difference waveguide.

33. The dielectric waveguide optical mode transformer of claim 32, wherein the first core material contains a taper decreasing in dimension in a vicinity of the first tapered region of the second core material before the first core material tapers outward.

34. A dielectric waveguide optical mode transformer, comprising:

a first dielectric channel waveguide including a low index core surrounded by a cladding layer;

a second dielectric channel waveguide including a high index core embedded at least partially within the low index core, wherein the low index core acts as a cladding for the second dielectric channel waveguide having the high index core; and

a transformer region, the transformer region being between the first dielectric channel waveguide and the second dielectric channel waveguide, wherein, in the transformer region, the high index core extends from the second dielectric channel waveguide and tapers

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downward to decrease in dimension so that the high index core has one end within the transformer region near the first dielectric channel waveguide, and wherein the low index core material extends from the first dielectric channel waveguide into the transformer region, embeds the high index core, and tapers outward to increase in dimension near the second dielectric channel waveguide, wherein the low index core extends beyond the taper of the high index core in the transformer region and forms the cladding for the

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second dielectric channel waveguide in a region beyond the transformer region in the second dielectric channel waveguide.

35. The dielectric waveguide optical mode transformer of claim **34**, wherein, in the second dielectric channel waveguide, the high index core is bound on top and bottom sides by the low index core.

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